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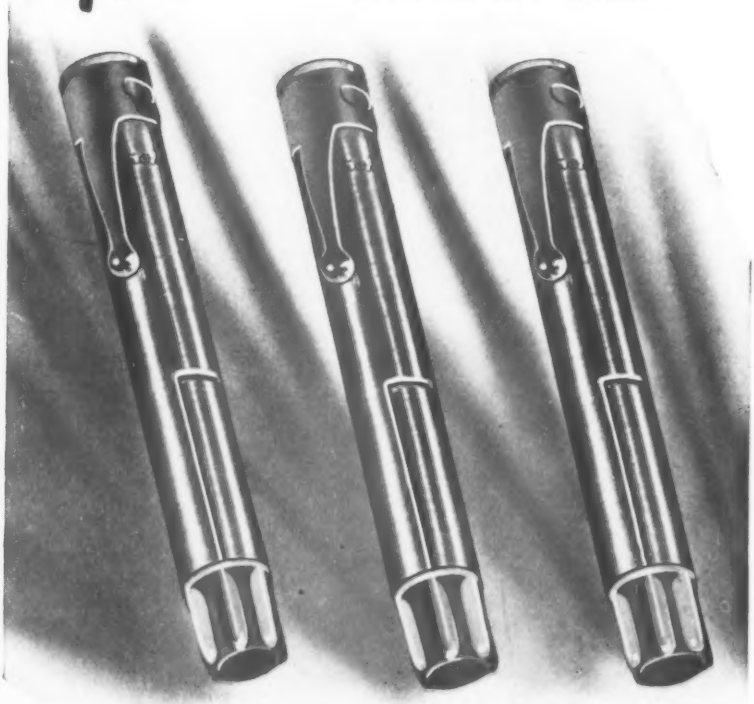

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NUCLEONICS

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Vol. 6, No. 4

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The Atomic Industry and Human Ecology

IX—SECRETS MUST BE KEPT

SECRETS MUST BE KEPT at whatever cost. This is the overwhelming public opinion in the United States according to replies from readers who were sent advance copies of the March editorial ("Never Point an Empty Gun") with a request for comment. Certainly this simple statement does not bear contradiction. And just as certainly it requires elaboration before it becomes useful in routine application, say, by the scientist and engineer who make discoveries and inventions and/or in the guidance of classification officers, reviewers, declassification officers, *etc.*

First of all, what is a secret? A very young friend replies, "A secret is something that two or three people know that they don't want anybody else to find out." The reader may also remember from his early school days, "We have a secret, just we three, the robin and I and the sweet cherry tree." And many of us recall from the United States Navy Regulations: "Secret matter is matter of such a nature that its disclosure might endanger the national security, or cause serious injury to the interests or prestige of the Nation or any Government activity thereof." These answers to the question (what is a secret?) contain the essence of what the people mean by secret in saying, "Secrets must be kept at whatever cost."

In order to help keep secrets, the Atomic Energy Act of 1946 proceeds to define *restricted data:* "all data concerning the manufacture or utilization of atomic weapons, the production of fissionable material or the use of fissionable material in the production of power, *but shall not include any data which the Commission from time to time determines may be published without adversely affecting the common defense and security*" (emphasis supplied). Then documents which contain restricted data are marked TOP SECRET, SECRET, or CONFIDENTIAL and are referred to collectively as "classified documents." Finally, those persons who handle any classified document whatever are issued copious instructions, some of which are also classified.

One notes a fundamental and terribly important difference between the definitions of "secret" as given above. In the one instance, any fact or document (*i.e.*, any "matter") which has been published, or otherwise become well known, or "disclosed" is *a priori* no longer secret. But from the viewpoint of the Atomic Energy Act of 1946, restricted data remain restricted data, and documents containing restricted data are consequently classified, *e.g.*, secret, no matter what their state of publication or disclosure, unless and until the Commission has itself determined that the facts in question may be published

without adversely affecting the common defense and security. It is presumably true, for example, that NUCLEONICS would be in violation of the law if it were to publish a manuscript submitted from Russia, say, which contained "restricted data." It is inconceivable to NUCLEONICS that public opinion would hold that secrets had not been kept, in the sense that the Nation was damaged, if such a publication were made.

H. G. Wells has written, "Essentially science is candour. . . . Man is born intricate, secretive and self-defensive, and he *learns* to become frank and simple. . . . Candour, like everything else worth while, is a thing to be achieved with infinite difficulty." These statements may not be in accord with the modern psychology in all details, but they convey an essentially true picture and illustrate why it is more difficult to obtain valid agreements with some peoples than with others. They illustrate how, for example, it was possible for one newspaper editor, so it has been reported, to assign a photographer to shoot a picture of General Groves handing over THE SECRET to Mr. Lilienthal on December 31, 1946. Most important of all, they illustrate why it is important that the people of this Nation learn all they can about atomic energy that is not secret.

It is particularly important that industry learn about atomic energy. Yet as things are presently, many industries, many teachers, and many men and women who would learn do not, simply because there is not enough they can be told that is not classified to cause them to want to. They cannot be shown what there is in it for them without *Q*-clearance, and they will not request *Q*-clearance. Some measure of personal gain, whether it be in dollars or position and power, or what not, remains essential. This is true even in war. In peace, or during a cold war, there is a great need for some recognition to accomplish what the Navy "E" accomplished, for example, when flown over plants in World War II.

Senator McMahon refers in a recent speech in New York to the possibility of a "Pearl Harbor raid against the United States (which), if successful, might cripple or even paralyze our matchless industry. There might then be no American industry to convert from peace to war." The unfortunate fact presently is that, in the sense in which the United States possesses a steel industry, an electrical and a chemical industry, *etc.*, *there is no atomic industry.* Whether or not there should be is, for the moment, beside the point. But as Senator McMahon proceeds to say, "The right to facts, the right to free circulation of news, the right to know is the most fundamental of all our liberties. Without it free speech lacks meaning, because the people have no substratum information on which to found an intelligent opinion."

Yes, secrets must be kept at whatever cost. And secrets can be kept only by a strong Nation, an informed Nation, a Nation that avoids a "Great Wall," whether it be of stone, as was that of China, or of an accumulation of paper work through which those who need to know simply do not have the time or the patience to wade. In order to make money, business men know, money must be used. In order to keep secrets, information must be disseminated. The parable of the talents is as true today as it was when Jesus taught; we cannot keep Nature's secrets by writing them down and stowing them away behind even the strongest doors or in the deepest vault.

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Education for the Atomic Age —A Psychological View

Considerations presented here were developed by Dr. Kay, a social psychologist, primarily on the basis of a series of studies of opinion and information about atomic energy. Intended to aid in tracing the development of attitudes toward a new social issue, data thus far gathered indicate that atomic energy is not a social issue independent of existing ones.

By LILLIAN WALD KAY

Department of Psychology
Washington Square College, New York University
New York, New York

IN THE PAST four and one half years there have been many references to the fact that we must prepare ourselves, and our children, to face the fact that we are now "living in the Atomic Age." What does this phrase mean?

In its narrower sense, it means that there have been, and will be, certain changes in various familiar areas of living which stem directly from the release of nuclear energy. The most significant, and possibly the most obvious, of these are:

1. The effect of the atomic bomb on warfare.

2. The changes in medical and industrial research and practice brought about by the large scale use of radioisotopes.

3. The possible development of a new source of power.

4. The development of a new type of executive-legislative relationship in Federal government as represented by the Atomic Energy Commission and the Joint Congressional Committee on Atomic Energy and a new type of peacetime government-industry relationship as represented by the AEC and its contractors.

5. In international relations, control of atomic energy is one—if not *the*—major issue around which East-West controversy in the United Nations has crystallized.

It may well be argued that there are parallels between each of these and earlier events which were not heralded as the beginnings of a new "age." Each war has seen the use of new weapons. Each generation has made its contributions to industrial and medical techniques. The relationships among the several branches of government are constantly being modified. In seeking an example of why major powers cannot agree, it is not unusual in international politics to focus on a specific situation. What is different about this?

All the other "ages" have been identified by historians in retrospect. Our awareness of living in a new era means that we recognize a major change that is more significant than just one more research tool or one more act of

Congress. It may be that the release of nuclear energy, coming suddenly as far as most people were concerned, is the symbol of an era in which science has become so important in our lives that all decisions, including political ones, must be made with scientific considerations in mind. This is the broader meaning of the phrase "living in the Atomic Age."

Three or four years ago many of us were writing that people were finding it hard to think in terms of nuclear energy because it had been thrust upon them so suddenly. The favorite comparison was with electricity, which had been introduced gradually. It now seems to be more than just the suddenness of nuclear energy being thrust upon the people. The age may take its name from the A-bomb, but it is characterized by the type of thinking necessary to deal with the H-bomb, bacteriological warfare, cosmic-ray research and at least one new "miracle" drug per week.

The *New York Times* (January 30, 1950), under the headline "Capital Is Held Ill-Equipped to Evaluate Bomb Issues," discussed a speech made by Dr. James B. Conant. Dr. Conant reportedly did not refer to the hydrogen bomb but did raise the question, "How are politicians to resolve conflicts of opinions among scientists and engineers?" This type of problem is met at all levels of today's living. It is to that growingly inseparable relationship between the technical and the social that we refer in discussing the Atomic Age.

To some extent this, too, is not a completely new or unique situation. Social scientists have frequently pointed out that technical advances, if they are to be accepted, must fit into the way of living of a particular society. We often hear that most of the contemporaries of Leonardo da Vinci honored his painting but ignored his scientific interests and achievements. By a small stretch of the imagination, we can see Leonardo today, honored as an engineer, his painting condoned as an interesting hobby—even as Einstein's violin.

Over the past two centuries in this country, as well as in western Europe, we have been moving toward increased mechanization and have been placing more and more value on technical progress. The developments of the past decade, epitomized by the atomic bomb, have brought us to the awareness that technology now has a unique position in our lives. In spite of the gradual approach to this point, which started with the Industrial Revolution, we are not quite prepared to face this fact. We have not been educated for it academically or politically. It creates problems.

Vannevar Bush has discussed (*1*) those problems from the point of view of the physical scientist who has had experience working with the "practical" men in government. His thesis seems to be that progress depends not on science alone, nor on democracy alone, but on the development of science in a democracy. Lilienthal has made much the same point in another context in statements to the effect that our democratic faith is stronger than our atom bombs (*2*). Sinnott (*3*) has suggested that an appreciation of scientific method by a large proportion of the population will help to preserve democracy by balancing enthusiasm and caution and eliminating the boredom which is, in itself, the product of technology. These are but a few instances of the fact that those people who have concerned themselves with technology and technological advances are cognizant of the unique relationship between social and physical science at this time.

Whether one starts from the more general definition of the Atomic Age which has been offered here, or specifically from a consideration of the release of nuclear energy *per se*, thinking

people agree that it is important for citizens in a democracy to understand the issues although they cannot, at this time, vote directly on most of them.

The remainder of this paper is devoted to an attempt to answer, from the psychologist's point of view, two questions: (1) Why is it important to be so informed? and (2) How can the job be done?

Why Stress Information?

The insistence on the desirability of informed public opinion with respect to nuclear energy stems from the basic belief that democracy functions best when the people understand the issues. This is obvious in a New England town meeting where people see each other coming out to discuss and vote. With state and national issues it is less obvious, as we do not have the experience of face-to-face participation or direct voting.

Why is it so important for the people to be informed about issues on which they have no apparent direct influence? The obvious reason is so that they can choose their representatives wisely. With respect to nuclear energy, these representatives, in turn, depend largely on such scientific information as is available to them. These policy makers must eventually answer to their constituents who can evaluate actions in Congress only if they themselves appreciate the issues.

Here, again, if it were only a question of intelligent citizenship it might be said that it is no more important for people to know the policies of the U. S. AEC than those of any other Federal agency. On the other hand, it might be argued that the U. S. position in other U.N. discussions is no less important than our position in the U.N. AEC. However, at this time, in addition to considerations of national security which currently focus attention on and give priority to an understanding of atomic energy budgets and policies, there are two other important reasons for stressing public information in this field.

The first has to do with the relationship between individual mental health and the problems of living in the Atomic Age. At best, life in a modern, complex civilization is a tense business. One reason many people find it so is that rapid changes make it hard to find emotional plateaus, although peaks and chasms are abundant. One need only examine the daily newspapers to confirm this. Nuclear energy, whether judged by itself or as the symbol of scientific advance, has been presented in extreme emotional terms.

An eminent scientist started a trend of looking askance with a piece entitled "I Am a Frightened Man," (4) which began "I write this to frighten you." A cancer patient, helped by radioiodine, wrote in a national magazine about owing his life to the A-bomb. The calm, if you will, the "scientific" approach, does not attract attention. One might have predicted a better sale for the book "No Place to Hide" than for "Must We Hide?" on the basis of titles alone. The best way for the individual to save himself from unrealistic despair, or equally unrealistic elation, in the field of modern scientific advance is for him to comprehend, to the best of his ability, what this advance means.

This leads to the second reason for stressing the value of informed opinion: the ability of the individual to plan for the future. We are not now speaking of the extreme emotional reactions to either the threat or the promise of scientific advance. Rather, the emphasis here is on issues like industrial and civic planning and vocational information for high school and college students. Will the development of nuclear energy change job possibilities? How? Will it add opportunities or merely redistrib-

ute manpower; at what levels of specialization will these changes occur? Where should new types of training be introduced? All of these questions—and more—will have to be answered for the young people who are planning their careers, indeed their lives.

In the field of civic planning, it will be increasingly important to consider the positive aspects of nuclear energy as exemplified by the possible use of nuclear fuels in power plants. On the other hand, civil defense considerations based on an objective appraisal of the possible occurrence and consequences of attack must not be ignored. Morale has been defined (*5*) as "a term which comes into prominence during crises when the conditions to which it refers are painfully absent or conspicuously present." At present the term may come into use only during crises, but it must be developed between these times. Community or national morale can be no better than that of the individuals comprising the group.

Developing an Informed Public Opinion

In order to be able to think, plan and vote with respect to these new issues, it is necessary to have an appropriate frame of reference. Just as a speedometer that does not measure speeds of over 25 miles an hour would have no place in a modern car, so ideas which provided a standard for judging social situations 40 years ago, indeed even 10 years ago, are inadequate in making judgments on some of these new problems. We need a point of view which, while incorporating our basic democratic values, gives guidance in evaluating the new problems.

Thousands of people in all walks of life were questioned by the writer for a period of over two years as to whether they thought they should have more information about atomic weapons, atomic power and "other uses" of atomic energy. Two points stand out. First, at least 60% of each group answered "yes" to the questions on weapons and more than 80% to power and other uses. Second, there were more "yes" answers to "other uses," when the respondent defined "other" as medical, than to power. It is our conclusion that the greater desire to learn about peacetime uses stems from two familiar points of view—the feeling that military matters are best left to the "experts" and the desire to be proud of the progress of American technology.

The greater concern about medical applications reflects still other familiar reference points—the fact that medical applications are already here and in use, and the interest in and concern for the highly personal problem of health. From the expressed interest and the familiar clues, it should be possible to create the necessary new frames of reference. That this has not happened is best demonstrated by some of the inconsistencies in public information and opinion revealed by research.

In November, 1948, 484 college students were asked to choose from a list of eight emotionally toned words the *one* "which best describes your reaction to the term 'atomic energy'." Another group of 565 was given the same task but the term was "nuclear energy." Which group a given student fell into was a matter of chance. There were significantly more choices of positive terms for "nuclear" than for "atomic" energy.

The public opinion polls also show apparent inconsistencies. The Gallup Poll has asked whether it was "a good or a bad thing" that the atomic bomb was developed. Presumably, if people think only in terms of the horrors of atomic warfare, the answers should be "bad"; if the judgments are based on the hope of peacetime development, they should be "good." If, on the other hand, the scientific point of view that the development was inevitable

prevails, either answer should have been rejected as based upon a false premise. The actual results (*6*) shown below suggest that "good" or "bad" judgments reflect other considerations:

	Good	*Bad*	*No opinion*
Sept., 1945	69%	17%	14%
Sept., 1947	55	38	7
March, 1949	59	29	12

Immediately after Hiroshima and Nagasaki, the answer was "good" by the largest margin, and the "no opinion" group was almost as large as the group answering "bad." In 1947, while the horrors of atomic war were being stressed and there were apparently good prospects for international control, the "bad" answers reached their peak and there were very few with no opinion. During the period of "cold war" the picture appears to be reverting to the 1945 pattern. These judgments, then, do not reflect an awareness of the meaning of the release of nuclear energy as much as they do other standards of judgment—in this case, the international situation. An analysis of the opinions of selected groups with respect to international control (*7*) indicated that old political patterns of isolation-intervention rather than the new explanations of the character of nuclear energy determined opinions.

An appropriate frame of reference has not developed for three major reasons. First, the problem of the inadequate dissemination of news through mass media. As it is released atomic information must be screened for newsworthiness in competition with other news. The problems of choice and the provision of background have been discussed elsewhere (*8*, *9*).

Second, community and school projects (exhibits, lectures, discussions, etc.) tend to emphasize either the physical or social science aspects (usually the physical sciences win out). The problem, however, is in the close relationship of the two. Yet of late one rarely hears discussions of the U.N. proposals in terms of the technical considerations of the two plans. The U. S. AEC reports no great trend to modify curricula to include nuclear energy (*10*). The *New York Times* on January 23, 1950, reported a general inadequacy in the teaching of current events because of the failure to integrate the new material into the school curriculum. Possibly one reason for failure in this area is that inclusion of these new materials would mean going across old disciplinary lines in a manner not provided for in current curriculum building practices.

Third, there has been little or no attempt to develop programs of education which appeal to specific groups. Within any community a men's lunch club will want different types of information from a women's group centering about a school. The college groups have a different starting point from that of people with an eighth grade education. When samples of the audience at the "Man and the Atom" exhibit were questioned before and after viewing it, sex differences were impressive not only with respect to what was felt and what was known upon entering the exhibit but also with respect to what was taken away in the form of new information and new points of view (*11*, *12*). Men were more hopeful than women before seeing the exhibit. They were also more hopeful after having seen it. However, within each group, there was an increase in hopefulness in the before-after comparisons.

There must be consideration of the fact that communities differ with respect to the current importance of nuclear energy to them in addition to the varied interests to be found within each community. It is too easy to disregard this and look upon one effective program as a blueprint for all. Even if some one exhibit or series of lectures could be taken to every town in the country, it could not possibly be of

RESULTS OF INTERVIEWS

The data tabulated below were gathered from two sources. Those under "Exhibit" list the results of interviews with people *entering* the "Man and the Atom" exhibit during its showings in New York, N. Y., in August and September, 1948, and in Cincinnati, Ohio, in November, 1948, and those entering the Brookhaven Nuclear Energy Exhibit in Wallingford, Conn., in January, 1950, and in Manhasset, N. Y., in February, 1950. The data in the "Student" group were gathered from New York University students in February, April, July and October, 1949.

The two sets of data are not directly comparable for the second and third questions. The people interviewed at the exhibits answered the questions without having had any alternatives presented. The students, who filled out questionnaires, may have had answers suggested to them by the manner in which the question appeared on the sheet.

1. ***Do you think you should have more information in the things you read and hear about (a) atomic weapons, (b) atomic power, (c) other uses of atomic energy?***

	Exhibits	Students
Number replying	3425	1155
a. *weapons*		
yes	64%	29%
security considerations qualify answers	12	52
no	22	8
no answer	2	11
	100%	100%
b. *power*		
yes	81%	57%
security considerations qualify answers	8	28
no	9	2
no answer	2	13
	100%	100%
c. *other uses*		
yes	83%	68%
security considerations qualify answers	7	22
no	7	1
no answer	3	9
	100%	100%

equal effectiveness all over. In a large and prosperous city, such a program might appeal primarily to "good citizen curiosity." In a smaller city which has, or anticipates, industrial use of nuclear products, a general program might serve as an ice-breaker. The real job is to prepare this community

2. ***Which of these words best describes your feelings when you hear the phrase "atomic energy"?*** (Respondent was asked to choose from this list: afraid, awed, bored, guilty, hopeful, insecure, justified, secure.)

	Exhibit	Students
Number replying	3425	1155
hopeful	30%	35%
awed	23	15
afraid	16	5
insecure	12	16
secure	8	1
all others (including no answer)	11	28
	100%	100%

3. ***For what things can atomic energy be used?*** (Because of some of the marked differences between the 1948 and 1950 exhibits group, the data have been separated.)

	Exhibits		Students
Year	1948	1950	1949
Number queried	3247	178	1155
Number replying	2749*	172*	1155
Uses			
medicine	50%	56%	61%
power	46	53	66
weapons†	37	28	96
industry	31	44	47
agriculture	7	21	56

* 498 in 1948 and 6 in 1950 answered "don't know." Number replying is used as base for calculating percentages.

† Many people at the exhibit chose to interpret question 2 as referring to peacetime applications.

for the special characteristics of the new work, particularly the problems of radiological safety and the necessary precautions to be taken. If such a situation also means the influx of a new population, then there is the additional problem of preparing to absorb that increase as well as the special problems of

nuclear products and byproducts. In the community with an urgent need (power is the best example), the citizens may look to these new developments as the answer to their problem. The biggest educational problem here is to keep from becoming too dependent on the idea of an immediate and easy solution which may not be forthcoming.

Although most people answer in the affirmative when questioned as to whether they think they should have more information about atomic energy, there is no evidence that they actively seek out that information. In fact, it would probably be easier to prove the opposite. Even if community and educational leaders were ready to plan programs intended to meet the needs of these many groups, it would still be necessary to learn how to create and maintain a high level of genuine interest of the majority of the population.

Since the President's announcement that we would proceed with the production of an H-bomb, many educators, editorial writers and civic leaders have commented upon the fact that this caused much less excitement than the dropping of the two "ordinary" atomic bombs. The implication is that the people have become "hardened." There are two other interpretations that are worthy of consideration. One is that a bomb—any bomb—dropped on people is different from a theoretical bomb, even if the theory is expressed in terms of what it would do to people. The other is that the information as to what the bomb will be like is hard to comprehend. There is no real evidence that the people have grown "hard" or that they are too frightened by the very idea of fission to become more frightened by this newer idea.

Having done considerable research using the question of emotional response to the term "atomic energy," we found that "fear" is not the outstanding or characteristic answer. That is reassuring in this period of tense international relations and the "cold war" because fear is debilitating. Yet we hear a great deal about how afraid people are of atomic energy. The source of this "information" is usually an editorial writer or commentator devoted to the idea that the best way to create interest is through fear. These people forget that panic behavior is rarely intelligent. Probably Cantril's study of reaction to Orson Welles' famous "Invasion from Mars" is the best evidence for this (*13*). The people who were responsive to the program in that they believed it unquestioningly did things that would complicate disaster relief in a real crisis. It is significant that Cantril found personality correlates for this non-critical reaction just as the British found that most of those who had marked emotional reactions to the bombings had other emotional problems (*14, 15*).

The present situation is too serious to take chances with national morale. Most discussions of morale stress the importance of realistic (not chauvinistic) confidence and information. It is toward these goals, rather than toward the multiplication of feelings of insecurity and futility, that opinion molders must move. Fear, confusion, misinformation and the feeling that "this is for Einstein, not me" are inadequate reference points that make it hard to interpret the news. All of these are against the best interests of the individual and the nation.

In a recent survey of opinion leaders on the subject of how to inform people with respect to these issues, the writer found that most of the answers stressed the use of familiar devices (radio, exhibits, lectures, etc.). In the use of these it is necessary not only to give information but, also, to strive to create the necessary standards of judgment. One way to do this is to plan programs so that they make an integrated unit of community activity. Where atomic

energy exhibits have visited cities, for example, there has usually been a civic proclamation of an "Atomic Energy Week." Atomic energy, however, symbolizes a way of living that cannot be dealt with in a week. What of next month or next year? It is too easy to say we "did" atomic energy if it is thought of as a "show" instead of having the show considered one item in a continuous chain of learning events.

Similarly, we must work toward finding some way of reporting news which will provide a growing backlog of information for the interpretation of the significance of these events without sacrificing the interest of the reader or making him feel that he must be a nuclear scientist to read a newspaper.

One area in which there has been some experience in providing background is in teacher education. An example is a course in which there is a series of lectures by more or less distinguished "experts," each of whom covers the highlights of his specialty. The audience comes away with a feeling of satisfaction because each member has added to his general information but there has been no integration nor has he been shown how to relate it to his immediate problem of teaching. With proper guidance, such a course might be excellent for a general community program.

Conclusion

We, in social psychology, have long since found that neither a "crowd" nor a "culture" can be separated from the individuals who comprise it. We have also found that selling ideas is a much more complicated problem in motivation than selling soap. Nationally, we are facing a critical time in selling democracy to the conquered nations and trying to preserve and strengthen it elsewhere. We must not forget the job of maintaining it at home. The creation of a feeling of crisis might be easy but would not, in the long run, be the effective way to maintain morale if we wish to continue to strive for peaceful solutions to the world's problems.

We have often heard that the consequence of stockpiling arms is the use of those arms. The consequence of stockpiling fear may well be demoralization. It would be tragic indeed if those two accumulations reached a peak at the same time. The physical scientist must continue his work in the combined interest of maintaining our national security and increasing our knowledge and well-being. The social scientist must stop uttering platitudes and increase our understanding of the problems of motivation and communication. If we combine our skills we may be able to build a stockpile of the most important commodity in a democracy in the Atomic Age—an informed and alert population.

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Nuclear Abundances and Closed Shells in Nuclei

The concept of electron shells was basic to the development of atomic physics. As outlined here, the shell concept has been extended by numerous investigators to nuclear particles. It is expected to lead to a better understanding of the nucleus.

By R. A. BRIGHTSEN

Department of Chemistry, Massachusetts Institute of Technology
Cambridge, Massachusetts

SINCE ABOUT 1917 there have been periodic attempts to observe regularities in the occurrence and abundance of stable nuclear species. This work was pioneered by W. D. Harkins, who is still active in it. Currently, while a moderate amount of attention is shown in the literature to abundance considerations, emphasis is being placed on the so-called "magic numbers"—proton or neutron numbers which exhibit unusual nuclear stability.

One can define the science of nuclear spectroscopy as the systematizing of nuclear species or nuclides based on nuclear properties. The already mentioned emphasis on "magic numbers" shows clearly that today effort is directed toward the discovery of the *pattern* of proton and neutron stability —the proton and neutron configurations which form closed shells. The concept of nuclear shell structure is essentially analogous to the familiar extranuclear electronic structures; one must keep in mind, however, that since nuclei are two-component systems (neutrons plus protons), the structural complexity is almost infinite compared to the "simple" electronic configurations. The present efforts in nuclear spectroscopy are in some respects similar to the pre-Mendeleev attempts to classify the elements.

Finding the stability pattern is important because it can be used to explain the present abundances observed for the stable isotopes. Ultimately it may be possible to postulate the distribution of species at the time of origin; if this can be accomplished, some logical speculations on the mechanism of formation—whether from a "neutron gas" or by fission—may be made.

Another important use of the stability pattern is to predict important nuclear properties such as slow and fast neutron cross sections, neutron and proton binding energies and magnetic moments.

The Stability Concept

The concept of stability is really the basis of all physical science. The tendency of all systems to reach the lowest energy state is universally recognized, but the relativity implication in the term "stability" is not nearly as widely appreciated.

A system is said to be stable when no change with time can be *observed*. One cannot make, therefore, absolute statements regarding stability; the best that can be done is to say that no detectable change occurs.

Some years ago Tolman (*1*) pointed out that the equilibrium between matter and energy lies markedly on the side of energy. This means that all mass is unstable with respect to radiation, and that the so-called "stable" nuclear species are in reality undergoing radio-

active decay on a time scale incomprehensibly large. Thus the least stable species are disappearing most rapidly and the most stable least rapidly; the transuranium elements undoubtedly existed millions of years ago, as did the "missing" elements Tc and Pm. Even the longest-lived Tc isotope, Tc^{99} ($T_{1/2} = \sim 5 \times 10^5$ y) has now disappeared, as have all shorter-lived activities that do not have precursors longer-lived than $\sim 10^8$ years. The only reason the short-lived elements of atomic number 80 or more still exist is because their decay rate is controlled by almost stable precursors.

An excellent example of a stable nuclide which is really unstable with respect to eons of time is Sn^{124}. Recently Fireman (*2*) found that this isotope undergoes a double beta transition (simultaneous emission of two beta particles from the nucleus) with a half-life of about 10^{16} years. This is the first known example of a phenomenon about which there has been much speculation in recent years. The role of very improbable transformations such as double-beta decay must be explained by any complete theory on the origin and evolution of the elements.

From the foregoing it seems philosophically logical to state that the abundance of a given nuclear species must be a direct measure of the stability of that particular configuration.* To test this hypothesis one should examine abundance curves (as functions of Z and N) to see whether high abundances are observed for nuclides having N or Z equal to known closed shells. If no exceptions are observed, more information on nuclear stability might be deduced from the curves. A comparison of this evidence for nuclear shell structure with other properties that reflect nuclear stability (isotopic cross sections, thresholds for nuclear reactions, natural radioactivity) will serve to elucidate the stability pattern.

MAGIC NUMBERS

The suggestion that certain neutron or proton numbers† represent especially stable structures was originally made by Bartlett in 1932 (*3*), and hence cannot be considered a recent idea. Revival of interest in this topic was accomplished by M. G. Mayer (*4*) in August, 1948, when she published a paper entitled "On Closed Shells in Nuclei."

The closed shell structures proposed by Mayer and some of the evidence upon which the proposals were made are listed briefly in the following.

$Z = 20$ (Ca). (a) The difference in mass number between the lightest and heaviest isotopes of Ca is eight; the difference in this region of the table does not exceed four.

(b) Ca has six stable isotopes (see Fig. 1).

$N = 20$. (a) Only three neutron numbers in the table of nuclear species are stable at more than one *odd* Z, namely $N = 20$($_{17}Cl^{37}$ and $_{19}K^{39}$), $N = 50$ and $N = 82$.

(b) A rather large number (five) of proton numbers are stable at $N = 20$ (see Fig. 2).

$N = 50$ and 82. (a) For even $Z > 40$ (Zr), the relative abundance of a single (stable) isotope does not exceed 35%, except in three cases: $_{38}Sr^{88}$ ($N = 50$, 82.74%), $_{56}Ba^{138}$ ($N = 82$, 71.66%), $_{58}Ce^{140}$ ($N = 82$, 88.49%).

(b) For even $Z > 32$ (Ge), the lightest isotope is not greater than 2%, except in five cases: $_{40}Zr^{90}$ ($N = 50$, 51.46%), $_{42}Mo^{92}$ ($N = 50$, 15.84%), $_{44}Ru^{96}$ ($N = 52$, 5.68%, unexplained), $_{60}Nd^{142}$ ($N = 82$, 26.80%), and $_{62}Sm^{144}$

* It should be noted that this concept has been assumed and utilized by Mayer (*4*) and assumed by Feenberg (*9*).

† The numbers proposed (*5*) were 2, 8, 10, and 20.

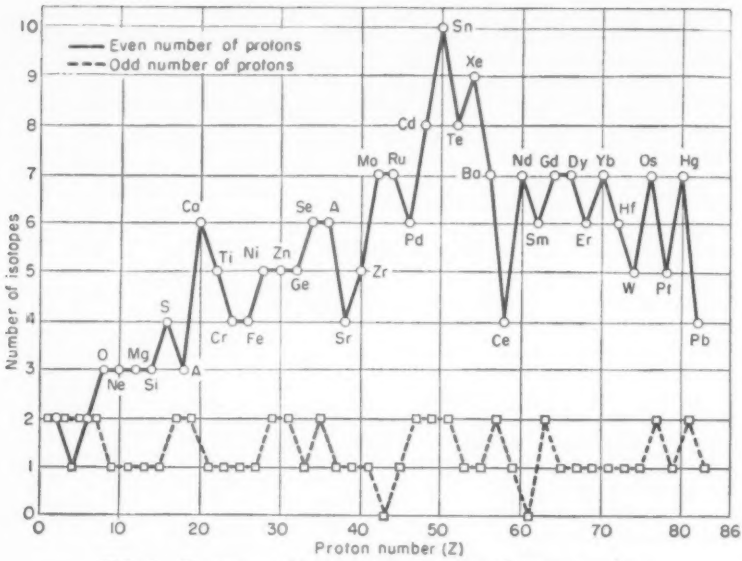


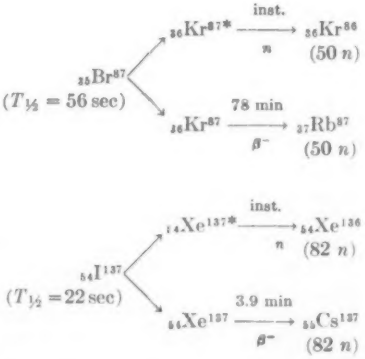
FIG. 1. Frequency of isotopes as a function of proton number

($N = 82$, 3.16%).

(c) See (a) under $N = 20$.

(d) Six* isotones (nuclear species having the same number of neutrons are called isotones) are found at $N = 50$ and seven for $N = 82$; see Fig. 2.

(e) If 50 and 82 neutrons form closed shells, then one would expect the binding energy of the 51st and 83rd neutron to be somewhat low. The only two† delayed neutron emitters thus far identified are $_{35}Br^{87}$ and $_{53}I^{137}$; these both emit beta particles and, since the excitation energy of the resultant nuclei ($_{36}Kr^{87}$ with 51 neutrons and $_{54}Xe^{137}$ with 83 neutrons) is greater than the binding energy of the 51st and 83rd neutron, achieve stability by emitting neutrons. Thus:



(f) The limits of stability for even-Z elements: The isotones $_{60}Nd^{142}$ (N = 82) and $_{62}Sm^{144}$ ($N = 82$) are both the lightest isotopes of their respective elements, while the isotones $_{40}Zr^{90}$ (N = 50) and $_{42}Mo^{92}$ ($N = 50$) are the lightest of these elements. The limit of

* One of these, however, is $_{37}Rb^{87}$ which is β^- active with a half-life of about 6×10^{10} y.

† One other case is known: N^{17}, with a half-life of 4.1 seconds, decays by β^- emission to $_8O^{17}$, which (?) then emits a neutron to become $_8O^{16}$ ($N = 8$).

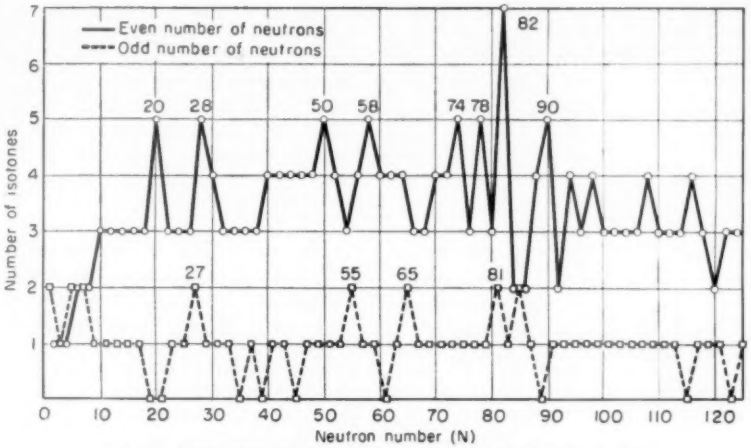


FIG. 2. Frequency of isotones as a function of neutron number

stability for neutron-rich isotopes is constant (for two even values of Z) at $N = 28$ ($_{20}Ca^{48}$ and $_{22}Ti^{50}$), $N = 50$ ($_{36}Kr^{86}$ and $_{38}Sr^{88}$), and $N = 82$ ($_{54}Xe^{136}$ and $_{56}Ba^{138}$), these isotonic pairs being the heaviest isotopes of the respective elements. Nowhere else in the table of species are the upper and/or lower stability limits constant.

$Z = 50$ (Sn). (a) Sn has the greatest number of isotopes (ten).

(b) Heaviest and lightest isotopes differ by 12 neutrons; Xe has the same spread (Xe^{124} to Xe^{136}), but this can be attributed to the stability of Xe^{136}, which has 82 neutrons.

(c) In a plot of elemental abundances versus Z, a peak is seen at $Z = 50$.

$Z = 82$ (Pb) and $N = 126$. Pb is the end of all naturally radioactive families; its heaviest isotope, Pb^{208}, has 126 neutrons and an abundance of 53.22%. Evidence (*5*, *6*, *7*, *8*) can be obtained from radioactive decay data for the stability of $Z = 82$ and $N = 126$.

In a more recent and theoretical paper, Feenberg and Hammack (*9*) analyze the data available on spins, magnetic moments, quadrupole moments, nuclear isomerism and β-decay and achieve considerable success in correlating these properties with the shell model. In addition to the structures already known (2, 8, 10, 20, 50, 82, 126), they propose two new structures and assign configurations utilizing the notation of atomic spectroscopy.

A closed neutron and proton shell at 40 is suggested, the reasons being that the magnetic moment of $_{39}Y^{89}$ favors the closing of the $3p$ shell at $Z = 40$; that in order to account for the high spin value ($9/2$) of $_{41}Nb^{93}$, it is necessary to postulate that the first $5g$ proton occurs at $Z = 41$; and that no stable species is known at $N = 39$ (see Fig. 2).

The $4d$ shell is stated to close at N or $Z = 60$; this is based on the facts that the spin value of $5/2$ for $_{59}Pr^{141}$ predicts the completion of the $4d$ shell at $Z = 60$, and that no stable species are known for N or $Z = 61$.

The configurations deduced by Feenberg for the closed shell structures are given in Table 1. Another excellent paper, by Nordheim (*10*), quite similar

TABLE 1
Closed Shell Structures

Shell	*Configuration*
2	$1s^2$
8	$1s^2\ 2p^6$
10	$1s^2\ 2p^6\ 2s^2$
20	$1s^2\ 2p^6\ 2s^2\ 3d^{10}$
40	$1s^2\ 2p^6\ 3d^{10}\ 4f^{14}\ 2s^2\ 3p^6$
50	$1s^2\ 2p^6\ 3d^{10}\ 4f^{14}\ 5g^{18}$
60	$1s^2\ 2p^6\ 3d^{10}\ 4f^{14}\ 5g^{18}\ 4d^{10}$
82	$1s^2\ 2p^6\ 3d^{10}\ 4f^{14}\ 5g^{18}\ 6h^{22}\ 4d^{10}$
126	$1s^2\ 2p^6\ 3d^{10}\ 4f^{14}\ 5g^{18}\ 6h^{22}\ 7i^{26}\ 5f^{14}$ $3p^6\ 4p^6\ 2s^2$

in context and conclusions to Feenberg's, should be consulted, as well as articles correlating "magic numbers" and nuclear properties (*11–16*).

An examination of Figs. 1 and 2 which show the number of stable isotopes as a function of Z and the number of stable isotones as a function of N, reveals certain interesting features. As Harkins (*18*) noted long ago, the stability range for even-Z and even-N species is much wider than for the odd-Z and odd-N nuclides. In Fig. 1 there is an apparent trend of the number of isotopes to a maximum at Sn and a subsequent decrease, on the average. Peaks can be seen at Ca ($Z = 20$) and Sn ($Z = 50$) in Fig. 1, while in Fig. 2 a pronounced maximum at $N = 82$ is evident (seven isotones) as are additional peaks at $N = 20$, 28, 50, 58, 74, 78, and 90.

The only place in Fig. 2 where an odd-N structure has as many isotones as the two adjacent even-neutron numbers occurs at $N = 85$ ($_{62}Sm^{147}$ and $_{60}Nd^{145}$). In this connection it is interesting to note that the alpha radioactivity of samarium is probably not due to mass 152 (*19*), despite the recent paper by Dempster (*20*) assigning it to Sm^{152}. Libby (*20*) claimed in 193[illegible] that natural neodymium showed a long-lived ($\sim 10^{10}$ y) beta radioactivity. These facts may have significance in this region.

It should be noted that any complete theory of nuclear shell structure will easily account for the missing neutron and proton numbers $N = 19$, 21, 35, 39, 45, 61, 89, 115, and 123; and $Z = 43$ (Tc) and 61 (Pm). The importance of the missing numbers has been almost completely overlooked by investigators to date, although Feenberg used the absence of N and $Z = 61$ and $N = 39$ as partial evidence for the stability of the 40 and 60 configurations. In a search for particularly stable nuclear configurations, marked instability should furnish important evidence.

Further, it seems evident that most investigators in this field have neglected the "overlap" effect which Townes (*11*) mentions: "Proton and neutron shells tend to be oriented or polarized to allow maximum overlap between proton and neutron distributions." Of course it must be understood that the evaluation of independent stabilization effects is a rather difficult task, in view of the statistically small variation of N for a given Z and *vice versa*.

Finally, the tacit assumption has been made by all the investigators to date that the proton and neutron stability patterns are the same, i.e., a number which represents a closed structure for protons is also a closed shell for neutrons. It may be that this is really the case, but it is by no means obvious. This tendency may be present, but it is likely that the degree of stabilization is different for protons and neutrons at the same shell edge.

ABUNDANCES AND PATTERNS

In a very recent paper, Harrison Brown (*21*) has critically surveyed the meteoritic and spectroscopic data available on the abundances (relative to Si)

of the elements in the universe and compiled a table of the best values available. A partial analysis of these data, based on the postulate set forth under "The Stability Concept," will be given.

For the elements utilized in this analysis, all abundances, except those for Ne, S, Cl and A, were derived from analyses of stony and iron meteorites; these data were considered more reliable than spectroscopic data. No experimental data are given for Kr, Te, Xe, Hg and Tl.

The values given are said to be, in general, accurate to within a factor of four, with a factor of two being the more usual error. Few limits of error are given, however.

Utilizing terrestrial isotopic abundances, the relative abundances of the nuclear species have been calculated and tabulated; in the cases so far investigated (Fe, Ni, Cu, Cr, Ga, C, O, Si, Cl, K, U and Co), no variations in the isotopic constitution of terrestrial and meteoritic elements have been noted, except minor differences in C. Insofar as the elemental data are sound, the isotopic abundances are reliable also.

In Fig. 3 Brown's data for the abundances of the elements in the universe are plotted on a semilogarithmic scale as a function of Z. Undoubtedly the most striking characteristic of the graph is the rapid decrease in relative abundance with increasing atomic number; the abundance ratio of Mg to Yb, for example, is about 6×10^5. This trend can be interpreted in a general way as a reflection of the nuclear instability due to the coulombic repulsion of the protons, this effect becoming more pronounced with increasing nuclear charge.

The systematic downward displacement of the odd-Z curve with respect to the even-Z curve is noteworthy; the pattern of one is almost exactly reflected in the pattern of the other. In this respect, several items require comment:

(a) Lu abundance seems to be too high; one might expect the relative abundance of this element to be equal to or less than about 0.0025.

(b) As is the only odd-Z element which is more abundant than its two even neighbors (Ge and Se).

(c) Certain numbers seem important. For example, minima on the odd-Z curve occur at Z = 31, 37, 43, 49, 55 and 61 (Δ = 6).

The periodic occurrence of maxima on the even-Z curve is, however, the most interesting feature of the plot. In accord with the statement (under "The Stability Concept") concerning the use of abundances as an indicator of nuclear stability, the ideal analysis of the data should be carried out in two ways:

1. A qualitative interpretation, in terms of closed neutron (and proton) shells, of the maxima on the abundance curve (Fig. 3) to obtain information as to the most stable nucleon structures; this sort of treatment is given in a later portion of this paper. A similar survey of the neutron analog of Fig. 3 could be carried out by plotting the *total* relative abundance of all stable nuclides containing a given number of neutrons versus the neutron number. After calculating the percent contributions to the total relative isotonic abundances of the several proton configurations, one can deduce the important proton (and neutron) numbers by inspections of the isotonic maxima.

2. A more valuable and rigorous treatment of the cosmic abundance data leads to an evaluation of the proton and neutron stability patterns; the stability curves obtained in this manner show interesting symmetry properties between pronounced maxima which represent closed nucleon shells. The distances between maxima provide information as to the relative stability of various energy levels in nuclei.

In this paper, the detailed analysis outlined cannot be undertaken. The derivation of the proton stability pattern is given in sufficient detail to illustrate the method used; the neutron stability pattern, derived in a completely ana-

logous manner utilizing isotopic abundances, is not treated in detail, but the closed neutron shells which result are discussed. The following summary is a brief qualitative interpretation of the abundance curve shown in Fig. 3.

1. Maximum at $Z = 10$ is due to closed proton shell in Ne^{20}, which accounts for 90.50% of the total abundance.

2. Peak at $Z = 14$ and maximum at $Z = 13$ is evidently due to neutron shell at $N = 14$.

3. Pronounced maximum at Fe is $\sim 92\%$ due to $N = 30$; probably there is a closed Z shell at 26 as well as a neutron shell at 30. Evidence for a $Z = 26$ shell is found in the maximum

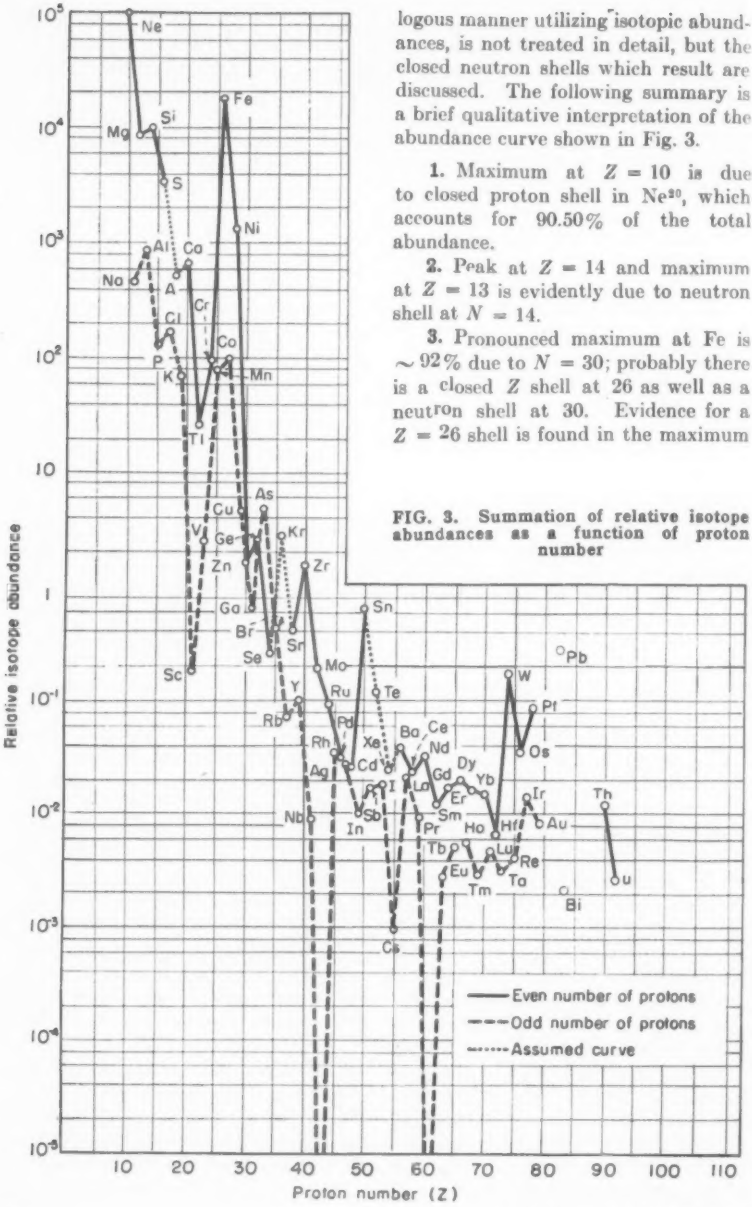


FIG. 3. Summation of relative isotope abundances as a function of proton number

at $_{27}Co^{59}$ for the odd-Z curve. Furthermore, if the neutron analog of Fig. 3 is plotted, a pronounced maximum is seen at $N = 31$ which is completely due to $_{26}Fe^{57}$.

4. Peak at $Z = 40$ (Zr) is due to 51.3% contribution of $N = 50$ as well as shell at $Z = 40$. The peak at Y ($Z = 39$) is also due to the 50-neutron shell.

5. The maximum at Sn is mainly due to the closed shell at 50 protons.

6. The peak at La is almost completely due to the $N = 82$ structure; the rise at Nd is partly due to $Z = 60$ and partly to $N = 82$. Nd^{142} contributes about 27% to the total abundance of Nd.

7. Peak at Dy is due mainly to $Z = 66$, with a contribution of $\sim 27\%$ from $N = 98$ (Dy^{164}). High abundance at Lu is apparently anomalous.

8. The high abundance of Ir ($Z = 77$) is due to high contribution (38.5%) from shell at $N = 114$. Peak at W ($Z = 74$) is due mainly to $Z = 74$ shell, with 29% of total abundance due to $N = 114$ structure.

9. Maximum at $Z = 82$ (Pb) is partially due to $Z = 82$ shell and partially (52%) due to $N = 126$.

Derived Proton and Nzutron Patterns

In the derivation of the proton stability pattern, it is necessary to utilize the total isotonic abundances. Since, at a given even Z there is a fairly wide spread of stable neutron configurations, a few unknown elemental abundances introduce uncertainty into a much larger number of isotonic abundances. In order to carry out this analysis it was necessary to estimate the cosmic abundances of several elements.

The elemental abundances of A, Kr, Te and Xe have been estimated by interpolation of Fig. 3.* The values obtained are (in atoms per 10,000 atoms of Si): A = 530, Kr = 2.7, Te = 0.12, Xe = 0.025.

TABLE 2
Percent Proton Contributions to Total Isotonic Abundances

Neutron Number	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
40	1.04	27.30	71.43	.....	0.23		
41			100.00				
42			16.00	83.44	0.40	.....	0.16
43					100.00		
44			36.55	.....	11.35	40.37	11.73

After obtaining the total relative isotonic abundances, the percent contributions of the several proton structures were calculated. For example, the total relative isotonic abundance at $N = 26$ is 23.422 ($_{20}Ca^{46} = 0.022$, $_{22}Ti^{48} = 19.1$, and $_{24}Cr^{50} = 4.3$; data from compilation of H. Brown). Thus the percent contributions are 0.09 for Ca, 18.37 for Ti and 81.54 for Cr. These data have been tabulated for $N = 10$ to $N = 114$; the data for $N = 40$ to $N = 44$ are shown in Table 2. Utilizing the data in this manner, one normalizes (or at least minimizes) the overlap effect and obtains figures which represent the relative stability of the proton numbers at a given neutron number.

To evaluate the over-all proton stability pattern, these percentages have been summed at constant Z; these values are given in Table 3 and are referred to as "proton stability indices." The *total* proton stability index (see Fig. 4) represents the sum of the contributions at a given Z for all stable odd and even-N species. This is obviously composed of the total proton stability index for odd-N, plus that for even-N (see Fig. 5).

The *average* proton stability index for even-N was then obtained by dividing the total (for even-N) by the

* See also reference *21*.

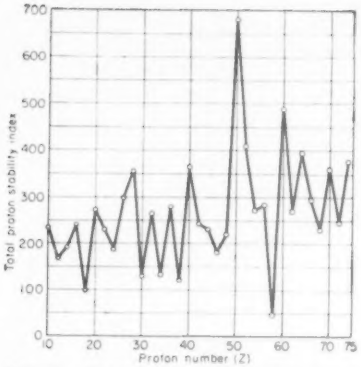


FIG. 4. Total proton stability index vs. Z

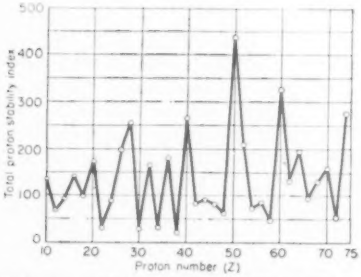


FIG. 5. Total proton stability index for even N vs. Z

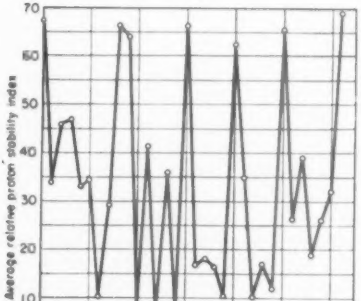


FIG. 6. Average relative proton stability index for even N vs. odd $Z/2$

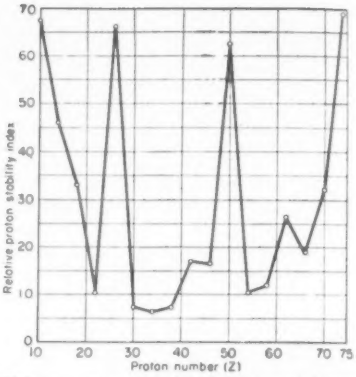


FIG. 7. Average relative proton stability index for even N vs. odd $Z/2$

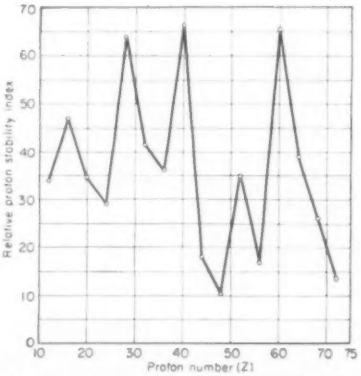


FIG. 8. Average relative proton stability index for even N vs. even $Z/2$

number of species of even-N stable at that Z. This index is plotted in Fig. 6, which is quite interesting, as it shows maxima at $Z = 10$, 16, 26 (28 is also high), 40, 50, 60 and 74. It is noteworthy that almost all the suggested magic numbers show up very well in this curve,* as do two of the configurations proposed earlier in this paper ($Z = 26$ and $Z = 74$).

In an effort to observe further regularities in the average proton stability

TABLE 3
Proton Stability Indices

Z	Total N Index	Total Number of Isotopes	Total Average N Index	Total Odd N Index	Total Even N Index	Total Number of Even N Isotopes	Average Even N Index, Odd $Z/2$	Average Even N Index, Even $Z/2$
10	235	3	78.3	100	135	2	67.5	
12	168	3	56.0	100	68	2		34.0
14	192	3	64.0	100	92	2	46.0	
16	241	4	60.2	100	141	3		47.0
18	99	3	33.0	0	99	3	33.0	
20	273	6	54.6	100	173	5		34.6
22	231	5	46.2	~200	31	3	10.3	
24	188	4	47.0	100	88	3		29.3
26	299	4	74.8	100	199	3	66.3	
28	356	5	71.2	100	256	4		64.0
30	130	5	26.0	100	30	4	7.5	
32	266	5	53.2	100	166	4		41.5
34	132	6	22.0	100	32	5	6.4	
36	281	6	46.8	100	181	5		36.2
38	122	4	30.5	100	22	3	7.3	
40	365	5	73.0	100	265	4		66.3
42	245	7	35.0	160	85	5	17.0	
44	231	7	33.0	140	91	5		18.2
46	183	6	30.5	100	83	5	16.6	
48	222	8	27.8	~159	63	6		10.5
50	679	10	67.9	~241	438	7	62.6	
52	410	8	51.2	200	210	6		35.0
54	273	9	30.3	200	73	7	10.4	
56	284	7	40.6	~199	85	5		17.0
58	48	4	12.0	0	48	4	12.0	
60	488	7	69.7	160	328	5		65.5
62	272	7	38.8	140	132	5	26.4	
64	396	7	56.5	200	196	5		39.2
66	295	7	42.1	200	95	5	19.0	
68	231	6	38.5	100	131	5		26.2
70	361	7	51.6	200	161	5	32.2	
72	247	6	41.2	192	55	4		13.8
74	377	5	75.4	100	277	4	69.2	

index for even N, Figs. 7 and 8 were plotted. Figure 7 shows the average proton stability index for even N for *odd pairs* of protons (Z = 10, 14, 18, 22, *etc.*), while Fig. 8 shows the same function for *even pairs* of protons (Z = 12, 16, 20, 24, *etc.*).

Pronounced maxima are seen to occur in Fig. 7 at Z = 10, 26, 50 and 74. Two points profoundly disturb the general symmetry of the curve—the high indices for Z = 42 and Z = 62. In Fig. 8 sharp peaks are found at Z = 16, 28, 40 and 60; again, the high index at Z = 52 disturbs the symmetry.

From these observations, a skeletal proton stability pattern can easily be deduced. Closed proton shells occur at Z = 26, 40, 50, 60 and 74, while a pro-

* Exceptions to this are Z = 20 and Z = 82; the latter could not be included because adjacent elemental abundances are not known. It should perhaps be noted at this point that M. G. Mayer has suggested (4) on theoretical grounds that a closed shell may occur at 28.

nounced subshell stabilization (see curves) is found at $Z = 28$, 42, 52, and 62. It is thus obvious that the most important proton shells in nuclei contain 14 and 10 protons (*f* and *d* levels in the nomenclature of atomic spectra).

In order to evaluate the neutron stability pattern, a completely similar analysis has been carried out utilizing the isotopic abundances. Although the stability curves obtained are not reproduced in this paper, the preliminary conclusions are sufficiently interesting to warrant consideration here. If the average neutron stability indices for even Z are plotted on two graphs, one for *odd* pairs of neutrons and one for *even* pairs of neutrons, symmetry properties again appear. After making corrections for the decay of K^{40} ($\sim 95\%$ β^-, $\sim 5\%$ *K*-capture) the following closed neutron shells are indicated by pronounced peaks in stability indices: $N = 14$, 30, 50, 66, 82, 98 and 126. It should be noted, however, that the peaks at $N = 66$ and 98, while quite definite, are not as pronounced as the others. The magic numbers proposed by Mayer ($N = 50$, 82 and 126) are clearly verified, as are those suggested ($N = 14$ and 30) earlier in this paper. The periodicity in the curve for even pairs of neutrons is somewhat less well defined, and requires further study. However, maxima are apparent at $N = 16$, 28 and 48. Thus it appears that adding 14 neutrons to an initially closed configuration of $N = 14$ or 16 produces stabilized structures at $N = 28$ and 30. The significance of the intervals of sixteen ($98 - 82 = 16$, $82 - 66 = 16$, $66 - 50 = 16$) is not obvious at the present time.

Conclusions

In the light of the derived proton and neutron stability patterns, it is necessary to conclude that the numbers that represent closed proton shells do *not* necessarily represent closed neutron shells, although certain numbers are peculiar to both (16, 28, 50 and 82). The correlations between closed shells in nuclei and nuclear abundances have been demonstrated, but many details and problems remain unanswered; among these is the consideration of the distribution of nuclei at some elapsed time after the formation of the elements which is short compared to the half-lives of certain nuclides now known artificially (Se^{79}, Zr^{93}, Pd^{107} and I^{129}).

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The author wishes to express his appreciation to Professors C. D. Coryell, C. Goodman, W. C. Schumb and J. W. Irvine, Jr. for advice and encouragement in the preparation of this paper.

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What Radioisotopes Can Mean to Industry*

Forecasting ever-increasing use of radioisotopes by industry, the author reviews their application to problems in petroleum chemistry, metallurgy, polymerization, lubrication, corrosion, electrochemistry, agriculture, animal husbandry, and food processing. Analytical radiometric analysis is outlined.

By CHARLES ROSENBLUM

Research and Development Division, Merck & Co., Inc.
Rahway, New Jersey

AN ANALYSIS of the nature of the applications of radioisotopes shows that they fall into two groups. In one group, the ionizing and penetrating power of the radioelement is the important consideration, whereas its chemical nature is immaterial.

Thus, we find that the radiations from radium and polonium have been employed (*1*, *2*) for years to ionize the air in the vicinity of moving machine parts and to dissipate the electrostatic charge which tends to accumulate in balance cases. A number of process control and other types of instruments, such as level gages (*1*, *2*), galvanometers (*2*), microbalances (*3*) and thickness and area measuring devices (*2*, *4*, *5*), have been constructed. Also included in this category are the location indicators and depth markers used for surveying and well-logging purposes (*5*).

The preponderance of past, and probably future, radioisotope applications, however, belong to the "indicator" or "tracer" group in which the chemical nature of the radioelement is the important factor. Here, the radiations serve primarily as a sensitive and convenient means of detection and analysis. The radiations constitute further the method for distinguishing the radioactive element from other elements, and from other isotopes of the same radioelement, present initially in the system. Depending upon the type of experiment performed, it is possible to determine physical and chemical properties, ascertain separation efficiencies and reaction yields, study various types of interfacial phenomena, follow surface and bulk migrations, investigate the mechanism of reactions, and measure reaction rates and equilibrium constants of physical and chemical processes. It is further feasible to perform measurements of utilization and turnover rates in an unequivocal fashion, and, in certain circumstances, to take advantage of a variety of versatile analytical procedures.

So far, anticipated industrial benefits from radioisotopes have been discussed only in general terms. A limited number of representative industrial uses selected from the technical literature will now be described in some detail. These examples are chosen, not because they completely solve a particular

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problem, but rather because they illustrate a principle in tracer methodology.* No pretense is made to complete coverage of any field or any problem. Original sources must be consulted for experimental details.

Petroleum Chemistry

In the field of petroleum chemistry, radioactivity has been used in studies of the mechanism of the Fischer-Tropsch synthesis (*6*) of hydrocarbons from mixtures of hydrogen and carbon monoxide in the presence of iron catalysts. Reactions for formation of unsaturated and saturated hydrocarbons may be written, respectively, as

$$n\mathrm{CO} + 2n\mathrm{H_2} = \mathrm{C}_n\mathrm{H}_{2n} + n\mathrm{H_2O} \quad (1)$$

and

$$n\mathrm{CO} + (2n+1)\mathrm{H_2} = \mathrm{C}_n\mathrm{H}_{2n+2} + n\mathrm{H_2O} \quad (2)$$

Until recently it was not uncommon to think of this reaction as proceeding by way of metal carbide formation and subsequent reduction of the carbide by hydrogen. Carbidization could conceivably result from reaction of the reduced metal catalyst with initially produced methane or with the carbon monoxide of the synthesis gas. The following reactions of the metal carbide with hydrogen would then describe the formation of olefinic and saturated hydrocarbons.

$$n\mathrm{Fe_2C} + n\mathrm{H_2} = \mathrm{C}_n\mathrm{H}_{2n} + 2n\mathrm{Fe} \quad (3)$$

$$n\mathrm{Fe_2C} + (n+1)\mathrm{H_2} = \mathrm{C}_n\mathrm{H}_{2n+2} + 2n\mathrm{Fe} \quad (4)$$

The intermediate carbide mechanism is susceptible to direct test by producing a carbide film on a metal catalyst by prior reaction with CO, and then passing synthesis gas ($H_2 + CO$) over the carbidized catalyst. If the carbide or the CO of the synthesis gas contained radiocarbon (C^{14}), the radioactivity of the products would indicate whether an intermediate reaction involving a carbide had occurred. In one set of experiments, a radioactive Fe_2C^{14} film was formed on an iron catalyst by reacting reduced iron with $C^{14}O$ at 200–270° C. This carbidized catalyst was then treated at ≈250° C with a synthesis gas mixture of hydrogen and normal carbon monoxide.

The initial products were collected, fractionated, and examined for radioactivity in a circulating gas counter after combustion of higher hydrocarbons to CO_2. A sample of the carbidized catalyst was also burned, and the radioactivity of the evolved CO_2 determined. For purposes of comparison, results were expressed as activity in counts per minute (cpm) per cc of gaseous product.

In the event that hydrocarbons were being formed exclusively by reduction of the carbide film, the specific activity of the initial products (cpm/cc) should be identical with that of the carbon in the carbide layer. These experiments revealed, however, that a considerable fraction of the C^{14} remained in the catalyst, and that the specific activity of the products was much less than the specific activity of the carbon in the carbide film. It was thus concluded that only a fraction of the hydrocarbon synthesis involved reduction of the iron carbide.

The inverse experiment, in which an iron catalyst previously carbidized with inactive CO was treated with a mixture of H_2 and $C^{14}O$, led to a similar result. In this case, the specific activity of the initial products should be much less than that of the $C^{14}O$ in the reaction mixture, since reduction of Fe_2C by hydrogen would yield a preponderance of inactive hydrocarbons. Actually, the diminution in cpm/cc was very small. For example, in one series of experiments, $C^{14}O$ containing 1,768 cpm/cc yielded a product with a specific activity of about 1,600 cpm/cc, a very

* In this article, discussions of industrial radiography and radiochemical reactions are omitted since these are independent fields and are not part of the subject under consideration.

TABLE 1
Solubility of Water in Benzene
(Gm Water/100 Gm Benzene)

Temp °C	*Radioisotope Method*	*Silver Perchlorate Solubility Method*	*Synthetic (Sealed Tube) Method*		*Absorption Method*	*Hydrogen Evolution Method*
10	0.030	0.043	0.040	0.035	0.032	0.045
20	0.0435 ±0.0010	0.057	0.056	0.055	0.044	0.057
26	0.054	0.070	0.070	0.069	0.057	0.067

small decrease, which indicates but a slight contribution from the carbide reduction step. By means of these experiments, Kummer, DeWitt and Emmett (*6*) concluded that some other mechanism than intermediate carbide formation and reduction is responsible for the greater part of the hydrocarbon synthesis in the Fischer-Tropsch process.

The preceding examples deal with the mechanism and rates of heterogeneous reactions in which conclusions are drawn from variations in specific activity (*i.e.*, changes in ratio of radioactive to normal isotope). Determination of physical or chemical properties by the radioisotope technique requires that the isotope ratio remain constant. A case in point is the series of measurements reported by H. S. Taylor and colleagues (*7*, *8*) of the rather low solubilities of water in various hydrocarbons for temperatures ranging between about 6° and 26° C. The radioactive tracer employed for water was tritium (H^3 or T) oxide present in heavy water to the extent of 10^{-12} mole of tritium per mole of water. The hydrocarbon was saturated with radioactive water at a desired temperature by bubbling air saturated with radioactive water vapor through the hydrocarbon sample until solubility equilibrium had been established. A measured volume of the saturated solution was then treated with dehydrated calcium oxide, the hydrocarbon removed by distillation, and the absorbed radioactive water exposed to ethanol vapor. By this means, the tritium was transferred by exchange to the alcohol vapors, the activity of which was then measured in an appropriate gas counter. From the total activity (cpm) of the ethanol vapors and the specific activity of the radioactive water employed (8.84×10^8 cpm/mole), the quantity of water dissolved in the hydrocarbon could be computed.*

Table 1 contains comparative results (*7*) obtained by the radioisotope method and by four other methods. Because of the ease with which losses of material by incomplete separation can be detected, one must attribute considerable reliability to the tracer method. Solubilities of water in a number of saturated and unsaturated aliphatic hydrocarbons have also been reported (*8*).

High Polymers

The role of polymerization catalysts and polymer size modifiers in polymerization reactions has, in certain cases, been difficult to elucidate because of inadequate analytical methods. With radioactive isotopes, it has been

* This computation involves the assumption that Henry's Law is valid and that the Henry's Law constant is the same for H_2O and TDO.

possible to study the incorporation of radioactive sulfur from persulfate initiator by polystyrene (*9*), of n-butyl mercaptan (*10*) sulfur in polymers of styrene, methylmethacrylate, methyl acrylate and vinyl acetate, and of persulfate, free sulfur and dodecyl mercaptan used for the emulsion polymerization of neoprene (*11*). Radiosulfur (S^{35}) was used in these experiments. The binding of m-brombenzoyl peroxide initiator during the styrene polymerization (*12*) has also been reported. In this case the bromine in the polymer was determined by irradiation in a neutron beam from a cyclotron, and the activity of the radiobromine produced determined. This procedure is called activation analysis (*13*) and involves the production of the radioisotope *in situ*.

The experiments of Mochels and Peterson (*11*) dealt with the role of $K_2S_2O_8$ initiator and of the modifiers dodecyl mercaptan and elemental sulfur in the emulsion polymerization of chloroprene. Polymerizations were performed at 40° C by addition of initiator and modifier (if desired) to the emulsion, except that the radioactive form of the particular substance being studied was added. In this way the origin of the sulfur in the polymer could be decided and the amount of sulfur from the radioactive compound determined with certitude. The radiosulfur present in any polymeric product, before or after fractionation, was determined by conversion to sulfate in a Carius tube and precipitation as benzidine sulfate, the activity of which was measured with a Geiger counter.

An understanding of the influence of sulfur on the chloroprene monomer was gained by radioactivity analysis of neoprene polymer separated into fractions of varying molecular weight. From this type of experiment it was found that 7–10,000 molecular-weight units were associated with each sulfur atom, which corresponds to an association of approximately 100 chloroprene units per sulfur atom. It was thus concluded that elemental sulfur reacts with chloroprene to form a comonomer which then polymerizes to form a copolymer.

In contrast to the behavior of sulfur, dodecyl mercaptan possesses the ability to control or modify the molecular weight of the polymer. It was found that the number of sulfur atoms (originating in the radioactive mercaptan) combined per polymer molecule was somewhat above unity (except in certain very high molecular weight fractions where values of 3–3.5 were found). Values above unity are indicative of cross-linkage formation, or addition of the mercaptan to double bonds. It appears that, in contrast to the function of elemental sulfur, the mercaptan directly influences the size of the resulting polymer.

Metallurgy

Radioisotopes have been employed in the solution of a number of problems (*14*, *15*) in physical and chemical metallurgy. A great many diffusion and self-diffusion measurements have been reported and summarized (*14*, *16*). No details will be presented here. It is in order, however, to point out that the radiations of a radioisotope provide a convenient and reliable method for following the inter-diffusion of two metals or salts, and that the isotope technique is the sole means of studying the self-diffusion of a given element or compound in a medium of the same composition. Diffusion studies in general illustrate the simplicity with which migration phenomena are observed if the moving component is radioactive.

A chemical investigation of metallurgical interest is the study by Winkler and Chipman (*17*) of the distribution of phosphorus between basic slag and liquid iron. Since equilibrium studies

were being made, it was necessary to decide how long the system had to be maintained undisturbed in order to insure reestablishment of equilibrium after addition of metal or slag, or after a system temperature change.

This information was obtained simply by heating a mixture of iron and a simple basic slag in an induction furnace to a constant temperature (say 1608°), adding a given weight of anhydrous tricalcium phosphate containing radiophosphorus (P^{32}), and taking samples of the molten metal at intervals of five minutes. The test samples were allowed to cool, and the activity of the solidified metal samples determined with a Geiger counter. Successive samples were found to reach a constant activity in about ten minutes, indicating that the phosphorus content of the liquid iron phase was no longer changing, *i.e.*, distribution equilibrium was attained in this time.

The effect of temperature change was observed by raising the temperature to 1660° and repeating the sampling and counting procedure. Again 10–15 minutes was found to be sufficient for equilibration of phosphorus between the slag and metal phases. This crucial orienting experiment was completed quickly and simply because the radiophosphorus eliminated the necessity for extensive analyses.

Friction and Lubrication Studies

Radioisotopes are admirably suited to these investigations because extremely small amounts of materials transferred between sliding surfaces can be determined accurately, and their paths on a surface traced by the radioautographic technique. Furthermore, it is possible to study frictional phenomena occurring at an interface between two blocks of the same material, in a manner analogous to the self-diffusion studies noted previously. The general subject of tracers in friction studies has been discussed at length by Burwell (*18*).

The work of Sackman, Burwell and Irvine (*19*), using a radioactive base and inactive spherical riders of various metals and glass, will serve to illustrate the method of determining the extent of material transfer to the rider. The friction base was a polished block of copper-beryllium alloy which had been irradiated in a deuteron beam to yield as an end-product a radioactive copper isotope (Cu^{64}). The activation was sufficient to permit the detection of 10^{-4} μg of metallic copper.

The Cu-Be block was fixed to a table. A spherical or hemispherical friction sample, held in the tool holder of a lathe attached to the same table, was slid mechanically over the base under varying conditions of load, distance and velocity of travel. The effect of these factors as well as of surface roughness, hardness and lubrication was investigated. Thus, $\frac{3}{8}$-inch diameter riders of phosphor bronze, steel, and glass, moving at a velocity of 3–4 mm/sec for a distance of 2 cm under a low load, collected 0.043, 0.0084 and 0.0053 μg of copper, respectively. Material transfer occurred in these instances and in every other case studied, even when very soft metals such as lead, or a non-metallic solid such as glass, was employed as a rider, at smallest loads and under lubrication. These experiments tend to prove that seizure and wear occur in all frictional phenomena.

Gregory (*20*) reversed this procedure by moving a radioactive lead (radium D obtained from old radon bulbs) rider over steel, copper and lead surfaces with and without lubrication. In all experiments, transfer of radioactive lead to the base metal was noted.

The effect of lubrication is demonstrated graphically by the radioautographs shown in Fig. 1. The radioactive lead rider was moved across a stationary steel base before (upper

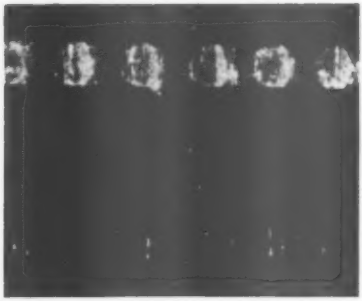

FIG. 1. Radioautograph tracks of lead sliding on steel (*a*, top; *b*, bottom)

strip, *a*) and after (lower strip, *b*) lubrication with 1% stearic acid in paraffin oil. The cleaned block was placed in contact with a photographic emulsion for several days, and the plate developed. This plate disclosed the location of all lead transferred from the rider, because the radiations from the radioactive lead exposed the photographic emulsion wherever they were in contact. The radioautograph reveals in striking fashion that sliding motion consists of alternate "sticks" and "slips," *i.e.*, a repetitive pattern of large areas of seizure, where material is transferred, separated by narrow areas where slippage occurs. Lubrication evidently reduces to a considerable extent the contact areas where material transfer takes place.

Corrosion Studies

Metal corrosion mechanisms are readily studied by incorporating a radioisotope of one of the alloy constituents in the system under investigation.

A case in point is the corrosion of a Zn-Al-Pb alloy in water vapor. Löhberg (*21*) employed the radioautographic technique to demonstrate the influence of lead on the corrosion susceptibility of the specimen. Thorium B was employed as the lead indicator in preparing the alloy. A radioautograph of the sample showed the lead to be located chiefly along the grain boundaries of the Zn-Al eutectic. Corrosion tests were then made by exposing the sample to water vapor for eighteen hours at 95° C. Comparison of the corrosion pattern with the radioautograph showed that the greatest attack occurred in regions where lead was concentrated.

Electrochemistry

The first radioactive tracer experiment was an electrochemical investigation performed by Hevesy (*22*) in which he showed that the relative amounts of lead and bismuth radioisotopes (B and C forms of radium, thorium or actinium) depositing from solution on an electrode without application of current was dependent upon the potential of the electrode in the particular medium. This observation was utilized in reverse to determine the emf of the Ta/Ta_2O_5 electrode.

A subsequent development reported by Hevesy and Paneth (*23*, *24*), while searching for electrochemical proof of the identity of isotopes, materialized as a test of the Nernst electromotive force law at very low concentrations of bismuth and lead ions, using their respective radioisotopes, radium E and thorium B, as indicators. The experiments with bismuth were extended to 10^{-12} *N* solutions by Haissinsky (*25*), using thorium C as indicator. The technique was applied by Flagg (*26*) for the determination of the standard potential of the masurium-permasurate electrode. These and numerous other aspects of electrode processes have been explored (*27*) with the help of radioisotopes.

Clark and Rowan (*28*) used thorium B to study the mechanism of plate reactions occurring in the lead storage battery. The accepted primary discharge reaction for the negative pole

of the battery is $Pb \rightarrow Pb^{++} + 2e$, and for the positive pole $PbO_2 + 4H^+ + 2e \rightarrow Pb^{+++} + 2H_2O$. At both electrodes, lead ions react with SO_4^- to form insoluble lead sulfate.

The original theory of LeBlanc (*29*) stated that the dissolved lead peroxide from the positive pole hydrolyzed to form plumbic ions which were not precipitated by sulfate. In this event diffusion of lead from the positive towards the negative pole should occur within the cell. All possible experimental conditions were tested, *i.e.*, charging or discharging to various degrees and in various sequences, having either electrode, or part of one electrode, radioactive, and using transfer of electrodes between cells. In no case was migration of radioactivity between electrodes or from one part of an electrode to another observed. In certain experiments, the electrolyte contained several percent of radioactivity, but this activity was separable by sedimentation, filtration or centrifugation and was due to crumbling of the electrode coating. A freshly charged, active PbO_2 plate immersed in fresh sulfuric acid contributed no radioactive lead to solution even when actually discharging, thereby eliminating the possibility of lead peroxide solubility as a factor. The inescapable conclusion of these experiments is that no detectable migration of lead ions occurs through the acid solution of a lead storage battery.

Agriculture and Animal Husbandry

The benefit to be derived from tracers in the study of agricultural and animal husbandry problems has been widely recognized. The ultimate goal of current programs is to determine most efficient fertilizer schedules and patterns and to devise means of evaluating soil fertility. Greatest interest to date has centered in the mode of utilization of phosphorus fertilizers, although work with other elements such as calcium (*30*), sulfur and arsenic (*31*) has been reported.

In general, the four variables listed in Table 2 have been considered in agricultural investigations reported to date. The first three types of experiments have been performed with radioactive superphosphate fertilizer. Case 1 is a comparison of fertilizer utilization by various crops. Case 2 is a study of the effect of soil fertility on fertilizer up-take. This type of experiment constitutes, in effect, a bioanalysis of the soil for phosphorus potentially available to the plant, as has been pointed out by Hendricks and Dean (*32*). Given comparable growing conditions and yield, as is possible in greenhouses, this technique could conceivably develop into a valuable and direct means of predicting soil fertility independent of chemical analysis.

The effect of increasing the amount of fertilizer on the growth of crops con-

TABLE 2
Variables in Phosphate Fertilizer Investigations

Case	*Crop*	*Soil*	*Fertilizer*		*Problem*
			Amount	*Type*	
1	Different	Same	Same	Same	Utilization by Crops
2	Same	Different	Same	Same	Soil Fertility
3	Same	Same	Different	Same	Fertilizer Rate
4	Same	Same	Same	Different	Efficiency of Chemical Forms

stitutes the type of study referred to as Case 3. No experimental details will be presented here.

The final type of agricultural experiment listed in Table 2 is a comparison of various fertilizers such as an intercomparison of inorganic phosphates, or a comparison of inorganic fertilizer with composts. A bare chemical evaluation of "available phosphorus" is misleading since the availability may be conditioned by factors such as soil acidity.

A direct comparison (*30*) between superphosphates and compost phosphorus was made in greenhouse experiments using rye grass as the test crop. Wheat was grown in a radiophosphorus fertilized soil, and the plants analyzed for total and radioactive phosphorus; *i.e.*, the specific activity was determined. This crop was then turned under and used to prepare a soil containing 65 pounds of P_2O_5 per acre. A similar plot was prepared with radioactive superphosphate. Rye grass was grown in both plots and the radioactivity of samples determined. Since the radiophosphorus uptake by the test grass was about the same in both plots, it was concluded that the phosphorus in the compost is about as efficiently utilized by plants as the phosphorus in superphosphate.

The preceding experiments depended upon the availability of a radioisotope which permitted a clear distinction to be made between added phosphorus and that initially present in the soil. Furthermore, all conclusions were dependent on changes in ratio of isotopic forms. These fertilizer experiments were essentially incorporation experiments, since radiophosphorus was always present in the soil.

Another useful kind of information obtainable with radioisotopes concerns the turnover (*33*) of an element or compound. Such information is of importance in biological systems since it is intimately related to the rates of

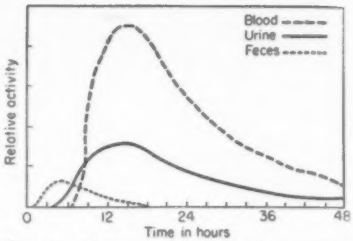

FIG. 2. Turnover of radioactive copper

renewal of all tissue components. The turnover rate is the net result of an incorporation and an elimination rate. Thus, an animal is fed a fixed but limited amount of radioactive compound, and then continued on a normal diet. The rate of accrual and ultimate diminution in activity of the various organs is a measure of the rate of replacement of the compound in these organs.

A representative experiment of this kind was described by Mahan (*34*) who was searching for compounds of copper, iodine, *etc.*, which were insoluble enough for inclusion in salt blocks for use by cattle, yet soluble enough to be physiologically active. A number of radioactive compounds were tested by feeding in capsules to heifers and determining the radioactivity of the blood, feces and urine over a period of several days. A plot of the data obtained with copper carbonate is given in Fig. 2. The urine and feces curves show that considerable elimination of copper starts shortly after administration of the carbonate and reaches a maximum rate in about 14 hours. The blood activity curve shows, however, that the carbonate is capable of providing physiologically active copper. The shape of the blood curve illustrates the initial build-up and subsequent decrease of copper which is characteristic of a turnover experiment.

Food Industry

The chemistry of foods, as well as their processing and utilization, constitutes another broad field for the employment of the isotope indicator technique. One application suggested by Spinks and Tollefson (*35*) is the rapid evaluation of the baking quality of flour by the extent of absorption of the radioactive ruthenium (Ru^{106}) ion. Adsorption isotherms were determined for various grades of flour in acid solution of ruthenium chloride. Results indicated that the poorer the quality, the greater the adsorption. Flour baking quality was judged by the size of bread loaves obtained, and by the amount of improving agent required to produce optimum loaf size.

My associates and I have just completed an extensive study of the fate of potassium iodate during the baking of bread (*36*). The iodate is incorporated in certain flours to improve the handling properties of dough. The amount added would correspond to 3–4 ppm of a finished loaf of bread. Attempts by standard methods to analyze the bread for iodate, and for iodide which one might expect to be formed, have been vitiated by reactions which occur during extraction.

To solve the problem of what happened to the iodate, we baked bread with potassium iodate containing radioiodine (I^{131}). Gaseous products were collected by absorption in alcoholic alkali and silver nitrate solutions, and their activities noted. Soluble components were extracted from the bread with aqueous ammoniacal methanol to which had been added inert potassium iodide and iodate to act as carriers for any free iodide or iodate which might be present. This extract was separated into a fat fraction, an iodide fraction and an iodate fraction, and the activities (cpm) of each noted. The extracted bread was also examined.

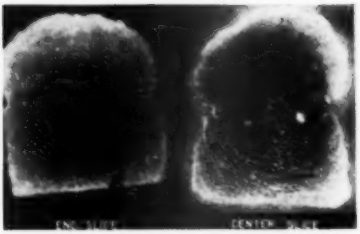

FIG. 3. Radioautographs of bread slices containing radioactive iodine (as iodate)

If any free iodate or iodide remained after the baking process, its presence would be revealed by the activity of the respective extract fractions. The activity of the fat, if significant, would represent iodinated fat, while the extracted bread, if active, might indicate the formation of iodinated protein. Furthermore, from a knowledge of the cpm of the added iodate, the percentage of initial iodine present in any of the above forms could be calculated.

Certain of our results are tabulated in Table 3. From these and other results, we were able to conclude unequivocally that the bulk (about 90%) of the iodine was recoverable as iodide, and that a maximum of 7.5% of the iodate was left unchanged. The activity of the gaseous products was negligible; the small amount of radioiodine in the fat fraction and bread residue probably represents incomplete extraction.

We employed the radioautograph technique as an incidental qualitative

TABLE 3
Summary of Baking Experiments

Experiment	*D*	*N*	*O*
Iodate	4.7%	2.7%	7.5%
Iodide	91.8	89.5	87.4
Residue	0	3.3	4.1

test of the iodine distribution in bread loaves. Exposures produced by a center and an end slice of one of our radioactive loaves are shown in Fig. 3. The presence of activity in both slices is obvious.

Miscellaneous

The preceding discussion admittedly has been far from complete and has failed to mention many large areas of industrial activity. Some of these other fields will be mentioned briefly here.

In the paint and pigment field, Buchdahl and Poleglase (*37*) have devised a method using radiophosphorus (as phosphorus pentachloride) for determining the thickness of printing ink and paint films. This information is needed for coverage and strength tests.

An example of the use of a radioisotope (C^{14}) in fermentation studies is the paper of Buswell and Sollo (*38*) on the methane fermentation of acetic acid. It shows that the methane is derived almost entirely from the acetic acid and not by reduction of carbon dioxide. In addition to investigations of fermentation mechanisms, radioisotopes can be employed to simplify the choice of desirable precursors for addition as broth components. The normal method of evaluating the utilization of a precursor of a substance like penicillin would be based on extensive but indirect studies of yields, which in turn are no better than the analytical methods available. On the other hand, if a radioactive form of the additive is furnished, indisputable evidence of utilization is provided by the radioactivity of the final product which need not be isolated quantitatively. A case in point is the biosynthesis of radioactive penicillin from sodium sulfate containing S^{35} by Howell, Thayer and Labaw (*39*).

In the field of industrial hygiene, Mortenson (*40*) has used radium D to facilitate the determination of the toxicity of lead tetraethyl vapors. The report by Barail and Pescatore (*41*) concerning penetration studies on cold cream tagged with C^{14} is of interest to the cosmetics chemist. The demonstration by Lerner *et al* (*42*) that a parenterally administered oil emulsion is metabolized at a rate of $\simeq$50% per day constitutes a pharmacological application. Finally, a discussion of the manner in which radioisotopes can serve the ceramics industry has been published by Johnson (*43*).

Analytical Procedures

A great many of the examples cited in preceding sections are essentially radiometric analyses for a particular element, and depend upon the constancy of the isotope ratio. Separation efficiencies, whether they pertain to a chemical analysis or a plant process, fall in this category. Erbacher and Philipp (*44*) used radioactive gold (Au^{198}) to test the completeness of the separation of gold from platinum and iridium, by a method in which the compounds are weighed after reduction to the metallic state. Such measurements can be taken a step further and used to correct the results of an erroneous analysis, as was done by Hevesy and Hobbie (*45*) in a series of rock analyses for lead content.

In contrast to the preceding, the analysis of complicated mixtures by the isotope dilution method depends on a change in isotope ratio. Although the method was first developed for stable isotopes (*46*, *47*), it has also been applied with radioisotopes.

The work of Sue (*48*) with radiopotassium will serve to illustrate the method. To a solution of alkali metal nitrates containing y grams of potassium (as chloride) was added x grams of radiopotassium, the specific activity [S_x(cpm/gm)] of which was predetermined. After mixing to insure homogeneity, the potassium was precipitated

as the perchlorate, a part of which was isolated in the pure state. Its specific activity was redetermined in terms of potassium content [S_y(cpm/gm)]. Since the specific activity of the x grams of radioactive potassium added was diminished by dilution with y grams of normal potassium present in the salt mixture, and since the total activity remains constant, we may write

$$(x + y)S_y = xS_x \qquad (5)$$

which leads to

$$y = x\left(\frac{S_x}{S_y} - 1\right) \qquad (6)$$

Since x and S_x are known for the radioactive indicator added, and since S_y is measured for the mixture, the weight (y grams) of potassium initially present is readily calculated.

The method has been tested by Henriques and Margnetti (*49*) with synthetic mixtures of the organic compounds dibenzyl sulfide, sulfone and sulfoxide. In these experiments, radiosulfur was used in the synthesis of all three compounds, permitting a complete determination for all components by the isotope dilution method. Excellent results were obtained. The average deviation between single analyses and the actual amounts added to these mixtures was 1.4%, and for the average of triplicate analyses, the average deviation was found to be 0.7%.

An obvious advantage of the direct isotope dilution method is that no necessity exists for the quantitative separation of any given component. One need only separate a quantity of component sufficient to assure its purity, as by melting point determination, and to permit a measurement of specific activity.

The reverse (*49*, *50*) of this procedure, involving the addition of inactive forms as diluents, can be applied to the analysis of reaction mixtures containing unknown amounts of radioactive substances, as may be necessary in animal experiments or mechanism studies performed with radioactive starting materials. Still another modification of the conventional isotope dilution method is available in the isotope derivative method of Keston, Udenfriend and Cannan (*51*), in which an inactive component of a mixture is reacted with a radioactive reagent to produce a radioactive derivative, which is then diluted with a large excess of inert form of the given derivative.

There always exists the possibility of developing rapid analytical methods based on measurements of radioactive elements. Stanley (*14*) has suggested such uses in connection with the analyses of steel. In the field of biological assays, Weissberger and Harris (*52*) have suggested measurements of the rate of excretion of radioactive strontium as a possible vitamin-D assay. Finally there is the method of activation analysis (*13*) for determining small amounts of elements (*53*) without recourse to standard, time-consuming chemical separations.

Conclusion

The preceding exposition illustrates the versatility of the applications of radioisotopes which are available to industry. These procedures may be applied either in the laboratory or in the plant.

One of the greatest potential industrial uses for radioisotopes is the determination of separation and isolation efficiencies where available analytical methods may be lengthy or of doubtful significance. As an example, consider a fermentation process in which the broth must be subjected to a succession of solvent extractions or adsorption steps prior to obtaining the final product.

Unless reliable analytical methods are available to assay the initial concentration in the original broth and to determine the quantity recovered at

each step of the procedure, the separation efficiency of the process is in doubt. On the other hand, if a radioactive isotopic form of the product is prepared, the process efficiency can be evaluated simply and in unequivocal fashion by adding the tagged product to a sample of broth and proceeding with the separation as usual. The radioactivity present at any given step indicates the fractional recovery at this point; the hold-up of product by a solvent or adsorbent is readily detected by its radioactivity.

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Localization of Radioactive Materials in the Phantom Brain

The method of localizing brain tumors with radiodyes reported in NUCLEONICS two years ago inspired the investigation here described. This variation of the technique —which may be called "tracer encephalography"—employs a rectangular system of coordinates and was derived from experiments with a balloon "tumor" in a plastic phantom "brain."

By Mark A. Griffin, Jr., Philip P. Goland, and Richard H. Chamberlain

Departments of Neurology and Radiology
Hospital of the University of Pennsylvania, Philadelphia, Pennsylvania

OCCASIONALLY space-taking intracranial lesions exist that cannot be diagnosed and localized by previously employed diagnostic methods—including air encephalography (*6*). In such cases, the use of the radioactive dye diiodo^{131} fluorescein first described by Moore *et al.* (*4, 5*) may prove helpful. With the presentation of its synthesis (*1*), the promise is held forth that a new safe test, which can be applied without discomfort to the patient, will be available for general evaluation.

Marvin and Moore (*3*), who used a phantom to explore the physical limitations of tracer localization, believe that the counter should be held normal to the skull while employing symmetrical counting positions. They state that such a method is preferable to moving the counter along a rectangular system of coordinates.

In the study* described here, a rectangular system of coordinates (orthogonal sets of axes) were used to locate concentrations of gamma-ray emitters. This method appeared logical on a theoretical basis and proves, in these experiments, to be more reliable for localization. The study was made with a phantom brain set into a skull.

Method

A hollow model of the brain was fashioned by forcing vinylite sheets, 0.60 cm in thickness, into molds of the base of the skull and calvarium. The two halves were cemented together.

At the center of the vertex of the phantom brain, a disk, 4.0 cm in diameter, was removed. See Fig. 1. A cylinder which extended above the

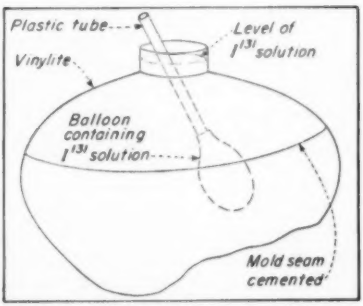

FIG. 1. Plastic "phantom brain" with balloon "tumor"

* Supported in part by Kirby-McCarthy Funds.

phantom was cemented around this opening. Through this opening at the vertex there extended a rigid plastic tube which was fitted to a rubber balloon filled with 40 cc of I^{131} solution. This volume was chosen since Marvin and Moore (*3*) believed from their experiments with the phantom that when the "tumor (or tumor plus edema)" approached 40 cc, it could be detected.

With this setup, it was possible to move the "tumor" into any quadrant of the phantom and to any desired depth. The balloon was filled with I^{131} solution having an activity per unit volume 2.5 to 5.5 times that of the fluid filling the remaining space within the phantom.

The phantom was set into the base of a skull and covered by a calvarium, perforated at its apex to accommodate the cylinder which was cemented to the phantom. About the skull was fixed a rigid rectangular frame, the "horizontal frame," which constitutes the "foundation" of the stereotaxic instrument devised by Clarke and employed by Horsley and Clarke (*2*) to make *spot* lesions at any known depth in the encephalon.

The horizontal frame was permanently joined to a collar frame. See Fig. 2. Another mechanism for supporting and moving the Geiger counter tube slotted interchangeably into the collar frame by removable pins. This mechanism is in effect a mechanical stage to move the Geiger counter through planes mutually perpendicular to each other by means of three screw-takeups.

An end-window Geiger tube was employed, encased in a heavy lead shield fronted by a shielding cone. In front of the tube window was placed a Lysholm-type grid constructed by two lead cylinders, 0.15 cm in thickness, equally spaced by two Plexiglas cylinders. See Fig. 3. This collimating device, 5.2 cm in length, had on its back face a 0.05-cm lead β-particle absorption plate. In the central axis of the grid, a sliding scale facilitated

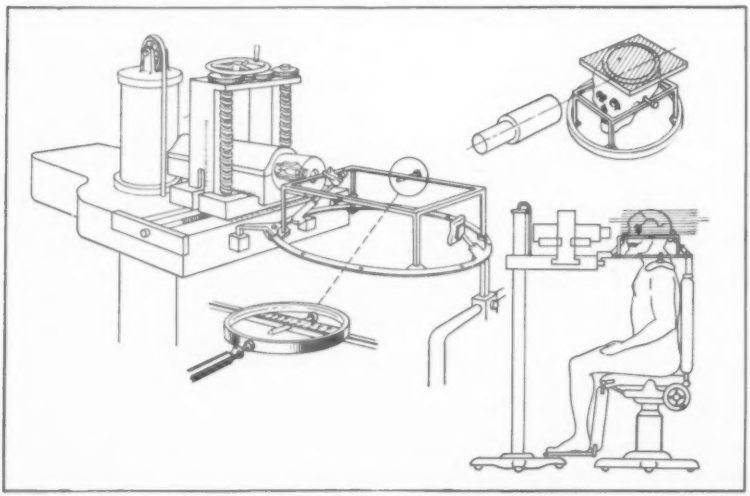

FIG. 2. Horizontal frame is joined to collar frame which sets into back of a Barany chair. Counter carrier slots interchangeably into collar frame

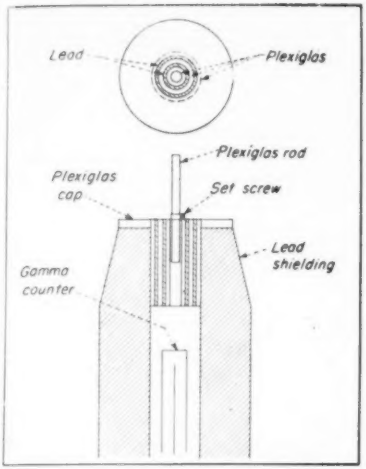

FIG. 3. Shielding cone with Lysholm-type grid

equal-distance spacing from the surface of the skull.

Counts were obtained with the balloon at various sites within the phantom. The results obtained by the use of the rectangular coordinate system (orthogonal sets of axes) were checked against the method employing symmetrical counting positions with the counter normal to the head, that is, the method of radians.

The centers of all "tumors" were traversed by one of three parallel planes situated 4, 7, and 9 cm above the horizontal plane established by the use of Reid's base line, *i.e.*, the line extending from the lower border of the orbit through the middle of the bony auditory meatus.

Figure 4 shows a horizontal plane of the head divided into four quadrants by the zero frontal and sagittal planes. Equidistant planes (1 cm apart), parallel to the zero frontal and sagittal planes, on crossing the horizontal plane, divide each quadrant into squares. By employing a system of Cartesian coordinates, the center of each "tumor" as given in Table 1 can be readily positioned.

If the center of the "tumor" were at the zero point (where the horizontal plane is crossed by the zero frontal and sagittal planes), it would be listed in Quadrants I, II, III, and IV at points 0,0.

The cross section of the aperture through the lead shielding cone and the square of the distance from the front face of the aperture to the "tumor" centers determine the solid angles subtended by the counter holder. (The counting rate increases with increasing solid angle.) Since the diameter of the aperture (4.8 cm) was greater than the diameters of the "tumors," the solid angle might, then, by reason of the inverse square law, be considered as being measured by $(\pi r^2)/h^2$, where r is the radius of the aperture and h is the distance from the front face of the aperture to the center of the "tumor."

The counting rate determined the location of the "tumor," the highest rates, of course, being observed in the quadrants containing the "tumors." The center of "tumors" were located by projecting two lines (*i.e.*, the central axes of the counter) where the highest counts were obtained when operating parallel to the frontal and sagittal planes. (In any single experiment, the counter moved only in the same horizontal plane.) These mutually perpendicular axes at their point of crossing within the head determined the "radioactive centers" of the "tumors."

The true position of "tumors" was located by a method which reduced the influence of the thickness of the subtended "slices" on the observed activity. Counts were taken (about the horizontal frame) of the phantom brain filled with the radioactive bath (without the "tumor") employing geometrical conditions similar to those used with the "tumor" *in situ*. When a ratio between the corresponding coordinates [("brain" plus "tumor")/"brain"] was

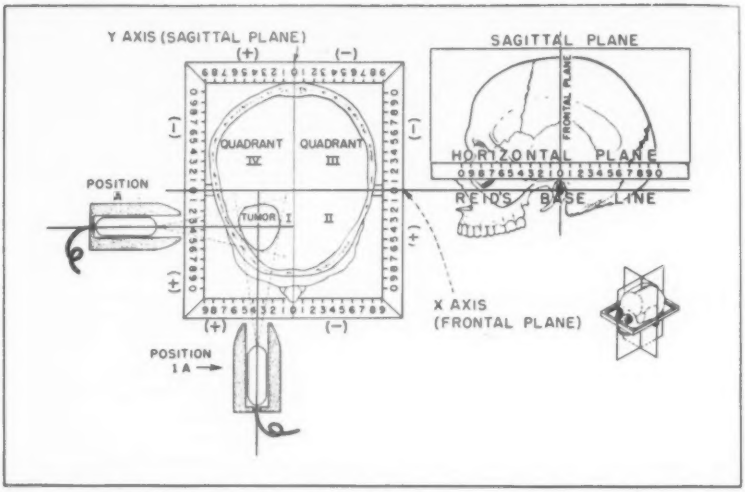

FIG. 4. Radioactive center of tumor is located by employing orthogonal sets of axes. Horizontal plane of the head is divided into four quadrants by the zero frontal and sagittal planes

set up, the true high peaks (radioactive center of the "tumor") became apparent.

The "tumors" were considered as having been located if the radioactive center lay within the circumference of the "tumors" as outlined on inspection. If the radioactive center lay outside of but near this circumference, the "tumors" were considered as being approximately located.

Two-minute counts were obtained in each position. Since additional time was required for making position adjustments, approximately two hours were spent in making a single survey.

The effect of variation in distance spacing upon the sharpness of localization was determined by the rate of fall of the maximal count to one-half value on moving the counter laterally off-center from the "tumor." The 40-cc "tumor"—surrounded by a non-radioactive bath—was placed at Quadrants III, IV, 0, −2 with its center traversed by the 9-cm plane. Counts were taken about the horizontal frame for each of the distance spacings from the skull of 4.5, 6.5, 8.5, 10.5, and 12.5 cm. The counts obtained on the occipital and right lateral sides were graphed. The distance from the maximal count (usually "tumor" center) to one-half value is presented in Table 2 for the various distance spacings.

Results

Table 1 summarizes the data on the phantom experiments comparing the methods of rectangular coordinates and radians. The "tumors" were located or approximately located in seven out of ten cases by the method of rectangular coordinates and were considered as being located in but three out of ten cases on employing the method of radians. In all cases in which the "tumor" was localized by the method of radians it was also localized by the method of coordinates.

In two cases in which localization was not obtained by the method of

coordinates, the activities of the I^{131} filling the "tumors" were of the lower order, 2.5 and 3.0 times per unit volume that of the "brain." Moreover, both "tumors" were deeply situated. In the third case, although the "tumor" activity was 5.5 times per unit volume that of the "brain," the shielding cone was spaced at a distance of 8.5 cm from the head so that the solid angle, measuring from the "tumor" center, was smaller than in any other experiment.

With these three exceptions, there was no difficulty in mapping out the "tumor" site even when the "tumor" was deeply (centrally) situated. If it was near the center with a greater portion to one side this was readily evident by considering the counts obtained along the other perpendicular coordinate.

In contrast, deeply (centrally) situated "tumors" could not be localized with certainty on employing the method of radians. As the "tumors" approached the center, the counts obtained on diametrically opposing sides of the head approximated each other and, in some cases, it was difficult to determine upon which side of the head the "tumor" was situated.

Discussion

The Horsley-Clarke stereotaxis instrument was modified to localize higher concentrations of radioactive material within the phantom brain. In a sense, the apparatus was employed in reverse to the use that it was put by Horsley and Clarke who used it to make localized lesions in the encephalon. The theory of operation of the instrument is based upon an arbitrarily established system of measurements.

The relation of encephalic contents need not be determined by variable external markings if the system of measurements called rectilinear cranio-encephalic topography is employed. This method depends upon the use of three mutually perpendicular planes (the coordinate planes). Any two of these planes intersect in a straight line which intersects the third plane at a point. If the zero point is arbitrarily located, any other point can be definitely placed by the method of section planing, *i.e.*, constructing planes parallel to the coordinate planes.

The line extending from the lower border of the orbit through the middle of the bony auditory meatus, commonly called Reid's base line, is employed to establish the zero horizontal plane. The zero frontal and sagittal planes along with the horizontal are mutually perpendicular, the three crossing at the zero point within the encephalon.

The rigid rectangular frame is employed similarly to its use in the Horsley-Clarke instrument to fix the head in a fixed constant relationship (symmetrically in the frame) so that this system of measurement can be applied. In place of the electrodes for making electrolytic lesions, we have substituted the Geiger-Müller counter.

An isotope that emits gamma rays is best for this method since they are rectilinearly propagated. Success in measuring such radiation depends on the energy range of the gamma emission, on the degree to which the radioactive isotope is localized in the area in question, and also on the depth of the lesion. The gamma-ray emission of I^{131} is sufficiently penetrating for this type of use. To the first approximation which neglects absorption and scattering, the rate of interception of the propagated rays will depend upon the solid angle subtended by the counter and the rate at which the rays are given off (*i.e.*, upon the total activity of the radioactive source).

By such collimating devices as the Lysholm-type grid in the aperture of the cone, attempts were made to obtain section planing (Fig. 2) as the

basis for location of "tumors" in depth.

The activities of "slices" of varying thickness through the phantom brain (containing the "tumor") were balanced by the activities of corresponding "slices" through the phantom (without the "tumor") by a ratio method. In this way the true high peaks became apparent, and, in a sense, measurements were obtained as if the "tumor" were isolated from the head.

An accumulation of radioactive material can be taken as placed at *A* in Fig. 4. Lines of tangency can be drawn to the circumference of this source. The intersection of these tangent lines form the apexes of solid cones. (The effective volume of the Geiger counter is taken as enclosing the apex of the solid angle of a cone.) As the collimation of rays increases, planar cones are approached whose surfaces are parallel to the zero horizontal, frontal, and sagittal planes.

The curved surface of the head is an irregular sphere. This fact precludes measurement from an arbitrarily established zero point by the method of radians. Measurement is dependent, therefore, upon variable surface markings since the surface of the head has few fixed points with the exception of the two points employed in rectilinear cranio-encephalic topography to establish Reid's base line. Symmetrical counting positions (with the counter held normal to the skull) probably could be obtained by holding the head symmetrically in a rigid frame marked for radian measurement. However, since measurements are obtained along single coordinates, the position of a tumor located by this method could probably only be described as being somewhere within a three dimensional cone.

We consider that the method of localization by rectangular coordinates employing orthogonal sets of axes offers some clinical adaptability as it now

TABLE 1

4, 7, or 9 cm plane (above Reid's base line)	*Tumor size cm²*	*Activity of "tumor"/"brain" (per unit volume)*
4	40	2.5/1
4	40	2.5/1
4	40	3.0/1
4	40	4.5/1
4	40	5.5/1
7	40	2.5/1
7	40	2.5/1
7	40	3.0/1
7	40	5.5/1
9	40	3.0/1
9	40	4.5/1

TABLE 2
Effect of Distance Spacing on Sharpness of Localization

Distance spacing from skull cm	*Distance to ½ Value (Count)*	
	Occipital cm	*Right lateral cm*
4.5	5.25	4.5
6.5	5.75	5.0
8.5	6.5	6.0
10.5	7.0	6.5
12.5	7.0	8.0

Rectangular Coordinate Method vs Radian Method

Solid angle $\frac{\pi r^2}{h^2}$	*Quadrant and Coordinates*		*Localized?*	
	Center of tumor (inspection)	*"Radioactive center" of tumor*	*Rectangular Method*	*Radian Method*
$\frac{\pi(2.4)^2}{(11.5)^2}$	IV, +3.5, −4.5	IV, +3, −7	Yes	No
$\frac{\pi(2.4)^2}{(11.5)^2}$	IV, +3, −1	IV, +6, −6	No	No
$\frac{\pi(2.4)^2}{(11.5)^2}$	I, II, 0, +2	II, −5, +2	No	No
$\frac{\pi(2.4)^2}{(11)^2}$	II, III, −3, 0	II, III, −5, 0	Yes	No
$\frac{\pi(2.4)^2}{(16)^2}$	III, −0.5, −3.5	III, −6, −4 III, −6, −0	No	No
$\frac{\pi(2.4)^2}{(9)^2}$	II, −3.5, +4.5	II, −4, +4	Yes	?
$\frac{\pi(2.4)^2}{(9)^2}$	II, −4.5, +2	II, −5, +5	Yes ?	Yes
$\frac{\pi(2.4)^2}{(14.5)^2}$	III, −1, −1	III, −3, −1	Yes	No
$\frac{\pi(2.4)^2}{(12)^2}$	I, +3.5, +3.5	I, +6, +6	Yes ?	Yes
$\frac{\pi(2.4)^2}{(12)^2}$	III, −1, −2.5	III, IV, 0, −4	Yes ?	Yes ?
$\frac{\pi(2.4)^2}{(14.5)^2}$	III, −1, −3	III, −3, −3	Yes ?	No

stands, but that an enlarged scope of usefulness will result from improvements in radiation detection and collimation apparatus.

Ill or unconscious patients could not be exposed to prolonged study with the head rigidly fixed in the horizontal frame. An apparatus, employing multiple counters, could be developed for more rapid measurements.

* * *

The authors wish to thank Dr. Park H. Miller, Jr., associate professor of physics, University of Pennsylvania, for the criticism of this work, and Mr. Anthony D. Calabro, Upper Darby, Pennsylvania, for fabricating the vinylite phantoms.

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FIG. 1. Complete apparatus. Mica-window beta-gamma counter is in right-hand side of lead shield. Preamplifier for alpha scintillation counter projects from shield at left

MONITOR FOR RADIOACTIVE DUST

Continuous collection of airborne-dust samples on filter paper is used for monitoring background. Apparatus can be used to determine decay periods and radon-to-thoron ratio.

By J. B. H. KUPER, E. H. FOSTER, and W. BERNSTEIN

Brookhaven National Laboratory
Upton, New York

FOR OBVIOUS REASONS, it is desirable to be able to continuously monitor the amount of radioactive dust contained in the air in the vicinity of a large laboratory or a nuclear reactor. In connection with the background monitoring program at Brookhaven we have had occasion to construct a number of continuous monitors which have proven useful in studying the natural radioactive background and its daily variations. Similar instruments are being constructed for monitoring the air in laboratories, and they may also have applications in other fields, such as prospecting.

In this instrument a strip of filter paper is moved, continuously, at a rate of about one inch per hour across an aperture through which air is pumped. This strip of paper, after collection of the dust, passes in front of one or more counters. The apertures of the counters are of approximately the same size

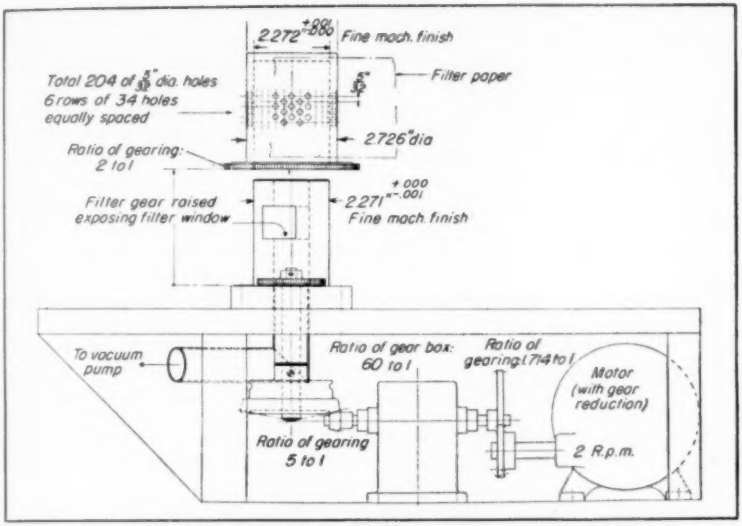


FIG. 2. Details of filter-paper drive and connection to air pump. Paper is moved one inch per hour; about five cubic ft of air pass through it per minute

as that over which the dust collection takes place, so that the counting rate, after correction for decay, represents a running average of the activity filtered out of the volume of air which passes through the paper over a period of approximately an hour—in our case roughly ten cubic meters.

Our standard arrangement comprises one mica-window beta-gamma counter which sees the dust sample about one hour after collection, and an alpha counter which sees the sample about four hours later. The alpha measurement is delayed to allow time for the RaB-RaC products to decay, but it obviously is not long enough to eliminate the effects of the ThB-ThC chain.

The apparatus is so designed that additional counters can readily be used, or the time sequence of the various counts readily altered from a minimum of about ½ hour to a maximum of about 18 hours following collection. We have found this feature of considerable value in enabling us to determine decay periods as well as to obtain information such as the radon-to-thoron ratio.

The arrangement of the apparatus can be seen in the photograph, Fig. 1. The two counters are encased in a lead shield. It is not necessary to enclose the alpha counter in shielding, of course, but this turned out to be the most convenient way of mounting it. The filter paper is driven by the capstan which is perforated by a number of 5/32-in. holes through which the air passes. The paper is sucked in slightly at the holes, thus furnishing a very positive drive with no tendency to stick at the air gate. It was found necessary to place the drive at the aperture in order to avoid breaking the paper in damp weather. The capstan is pivoted on an inner sleeve and is driven by a gear at its

lower edge. As indicated in the sketch, Fig. 2, the inner sleeve is perforated with a rectangular aperture one inch high by $1\frac{1}{16}$ in. long and a connection to the inside is provided for the air pump. It was found that a sufficiently good seal could be made by greasing an ordinary machined surface.

After passing in front of the counters, the paper is led around an idler pulley and then to the take-up drum which is driven by a rubber belt and friction disk. Suitable reduction gears are provided to drive the capstan from a synchronous motor, giving the desired paper speed of one inch per hour. At this speed, a full roll of paper, as supplied on special order by the manufacturer, lasts for approximately six months. The air flow is about 5 cubic feet per minute, with a pressure drop of approximately five pounds per square inch at the paper. Since we are continually presenting a fresh surface of filter paper, we have so far experienced no trouble due to dust collection plugging up the filter paper pores and diminishing the air flow, although in very dusty atmospheres it might be necessary to speed up the paper drive.

For the beta-gamma counter we have been using the conventional mica end-window variety. Because of the possibility of spurious discharges arising from electrostatic charges on the filter paper, we feel it would be desirable to have a counter with a conducting window, but preliminary experiments in building counters of this type have not been encouraging. For counting of alpha particles we have chosen a scintillation counter using an activated zinc sulfide screen on the end of a 5819 photomultiplier tube. This counter enjoys the great advantage of almost complete immunity to microphonics or electrical disturbances, so that the background counting rate is quite low, between five and ten counts per hour. The zinc sulfide screen is covered with a double thickness of aluminum foil (0.3 mg/cm^2) to exclude visible light. The pulses obtained from the 5819 operated at from 600 to 900 volts are large enough without additional amplification, to trigger most scalers intended for use with Geiger-Müller counters. However, the scalers employed in our installation require a signal of about 1 volt for triggering, so we have employed a stage of amplification.

In Fig. 3, we show a sample record of the natural radioactive background observed in the course of a week. Measurements of half-life indicate that the activity in the peaks decays with the lifetime of thorium B, and comparison of records taken simultaneously at stations separated by several miles indicates that the fluctuations in the background activity are of a general rather than local character. We have found a striking correlation between the appearance of peaks in activity collected with dust and meteorological conditions. The peaks are associated with periods of relatively calm air accompanied by an inversion in

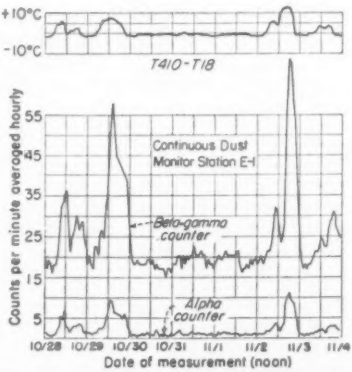


FIG. 3. Sample record obtained during week of October 28–November 4, 1949. Note that peaks in beta-gamma and alpha curves coincide in time with the temperature inversions observed between the 410 and 18 ft levels of the meteorology tower

the lower atmosphere, as evidenced by the upper curve showing the temperature difference between elevations of 410 and 18 feet. It seems reasonable to suppose that the emanations or dust bearing "active deposit" are trapped near the ground by the temperature inversion, instead of being permitted to diffuse into the upper atmosphere. So far we have not been able to find any correlation between activity collected and the general dustiness of the atmosphere (occasioned by building operations or dense chimney smoke) as judged from visible blackening of the paper.

The mechanism of collection of the active deposits is not well understood, but it is surmised that it results from attachment of the deposit to dust particles in the air. The decay of an atom of thoron will lead to an ionized atom of thorium A, which may attach itself by image forces to a dust particle. If, perchance, the thorium A is neutralized without attachment, there is a chance for repeating the process when it in turn decays to thorium B. Similar relations are to be expected, of course, in the radium chain. What fraction of the thorium A atoms become attached in this fashion we do not know, but experiments are in progress to determine this point.

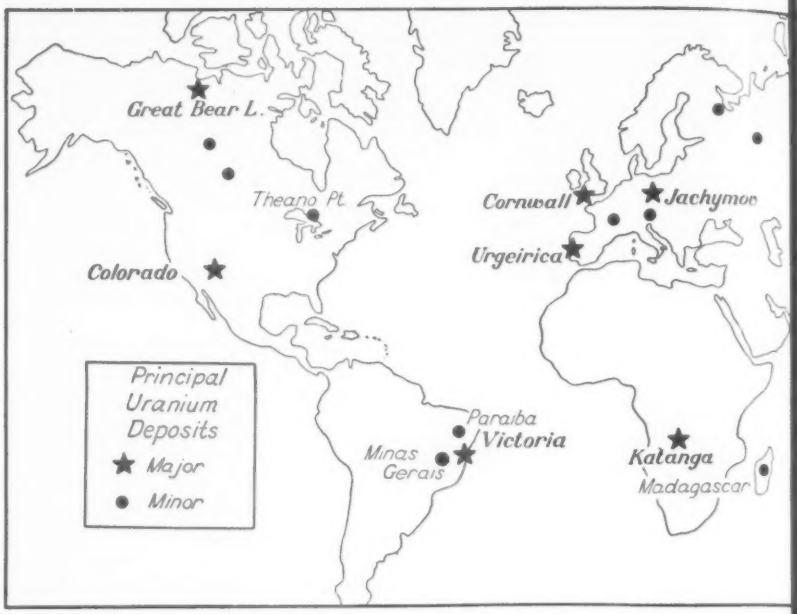
* * *

It is a pleasure to acknowledge the assistance of our colleagues in the Electronics Division, particularly Mr. R. Dillingham of the shop, and Mr. Douglas Clarcus. This work was supported by the Atomic Energy Commission.

Mechanical Engineering in Atomic Energy

If the atomic energy industry, particularly in the power field, is to be successful, the mechanical engineering profession has a tremendous job ahead of it. We must learn how to handle liquid metals at high temperature. We must solve the problems of heat transfer rates which at the present time seem out of this world. We not only must learn how to build these atomic power plants at an economical figure, but we must also learn how to operate them economically and how to maintain them over long periods of time. The stress analysis work, the heat transfer work, and plain mechanical ingenuity required to pump liquid metals, to say nothing of the problems of how materials behave under intense radioactivity, are all major mechanical engineering problems. Those of us in the atomic energy business feel sure that these problems will be solved, but we know that it is no easy job, and that atomic power is certainly not just around the corner.

—R. S. Neblett, General Electric Company, in talk before Machine Design Division of A.S.M.E., Washington, D.C., January 26, 1950



The Occurrence of Uranium

By GEORGE H. T. KIMBLE and MARTIN H. SINCLAIR

McGill University
Montreal, Canada

CONTRARY TO popular belief, scientific interest in uranium is by no means new. In 1789 Morton Heinrich Kloprath, a German chemist, is said to have discovered an oxide of uranium. The element was isolated in 1842 by Peligot. In 1896 Henri Becquerel initiated the study of radioactivity which led to the discovery of radium in pitchblende.

Before World War II the demand for uranium ores was mainly for the production of radium, certain types of ceramics and for research purposes. The quantities needed were so small that two producing regions, the Katanga district of the Belgian Congo and the Great Bear Lake area in northern Canada were able to satisfy the world demand. But now there is a question of whether supply will keep up with demand.

Uranium Family

Natural uranium consists of 99.3% U^{238}, 0.7% U^{235}, and 0.006% U^{234}

U^{235}, which is unstable, was first identified by A. J. Dempster in 1935, but was not used on a practical scale until the war.

U^{238} is not fissionable, but can be converted into the unstable U^{239}, and then into the fissionable plutonium. U^{239}, as well as U^{237}, can be produced in the laboratory, but neither is believed fissionable. U^{233}, which is fissionable, is produced from thorium. U^{234}, formed in the laboratory, is reported to be incapable of releasing atomic energy. Chemists suspect there is a seventh member of the uranium family, U^{236}, which may exist for very short periods of time.

Geological Characteristics and Occurrence

Pure uranium has an atomic weight of 238.07 and is thus the heaviest known metal. White and slightly softer than steel, it has a specific gravity of 18. It is also one of the more common metals, being almost as abundant in the earth's crust as copper. It has been estimated that in a million tons of the earth's crust there are four tons of uranium. However, because it seldom occurs in sizeable concentrations, and never in a pure form, the task of the uranium prospector is far from easy. Nor does the wide geological occurrence of the mineral do anything to facilitate the prospector's task. High quality deposits have been located in rocks of various ages.

More than one hundred minerals carrying uranium have been described in mineralogical literature. Among the more common are pitchblende, uraninite, betafite, and euxenite, which are classed as black minerals; carnotite, tyuyamunite, autunite, yellow in color; and meta-torbernite and torbernite, green minerals. It is customary to divide these uranium minerals into two categories, primary and secondary. The former are those which have not been changed since they were originally deposited, while the latter have been produced from the primary either by weathering, or as a by-product of ground water circulation.

The primary uranium minerals are usually found in pegmatites or veins and are generally heavy and dark in color (dark brown or black) with a dull, pitch-like luster. As they decompose easily to form secondary minerals, they are rarely found in surface rocks exposed to weathering.

The secondary minerals have rather different characteristics. They are found in almost any type of rock (not necessarily associated with primary minerals) and in the form of earths, powders and flat plates. The predominant colors are bright yellow, orange and green.

Until the mid-1940's the demand for uranium was met quite adequately by processing vanadium and radium ores,

and thus there was little incentive for prospecting. Today the position is very different: every lead, no matter how unpromising or how old, is checked thoroughly. The location of one deposit (Theano Point, Ontario) was established on the basis of a report made by a geologist (J. L. LeConte) as far back as 1847!

Regional Occurrence

Two difficulties face the compiler of data on the regional distribution of uranium deposits. In the first place, few nations are willing to reveal specific information on the location of such deposits; and secondly, where such information is available, there is almost no way of distinguishing between significant and non-significant finds. In the provinces of Saskatchewan and Ontario alone over 45,000 uranium claims have so far been granted, but it is probable that not more than a dozen or so of them will prove to be economically exploitable.

Africa. The Shinkolobwe mine in the Belgian Congo, discovered in 1915 by Major Sharp while searching for copper, is usually regarded as possessing the largest known uranium deposits in the world. By 1921 it was found that the ore bodies were sufficiently rich to enable the Union Miniere du Haut-Katanga to capture the world's radium market. This virtual monopoly of radium was ended in the 1930's by the development of the Eldorado mine in the Northwest Territories. At the present time the producing company has plants at three sites, viz. Lubumbashi, Jadotville-Panda and Shinkolobwe. The only other African mines believed to be in operation now are in central Madagascar: betafite is mined at Ambatofotsy and Amparitena, autunite in alluvium of the Fitamalama River and euxenite in the vicinity of Ankazove. Production, however, is on a small scale, and there has been little systematic exploration of the sites up to the present time.

North America. Gilbert LaBine, in his search for cobalt and silver in 1930, accidently found one of the richest known deposits of pitchblende on the east side of Great Bear Lake, Northwest Territories. This was the basis of the Eldorado Mining Company, which by 1939 was yielding radium, uranium, silver and other minerals valued at $300,000 monthly. Its annual report for 1948 disclosed that it had extracted $1,000,000 worth of atomic energy raw material.

The two minerals found in the United States which contain workable quantities of uranium are carnotite and pitchblende. Carnotite deposits are widely distributed throughout the Colorado Plateau over an area covering some 50,000 square miles in western Colorado and eastern Utah. Some of these deposits were known as far back as 1903. The area was exploited until 1923 for radium and again thirteen years later for vanadium. The production decline in the interval was due to the more profitable developments in the Belgian Congo. Today it is estimated that there are some 300 mines operating in the Colorado Plateau, making the region the main source of uranium supply in the U. S.

South America. It is known that there are many uranium mineral deposits in Brazil and attempts are currently being made to determine their quality and extent. Samarskite and euxenite occur in some of the beryltantalite pegmatites of Minas Gerais and Paraiba.

Eurasia. The first uranium ores ever to be extracted were those of the Erzebirge region at Jachymov (Joachimsthal). This area had been mined for tin in the twelfth century and later was famous for its sustained silver and cobalt output. In the middle of the nineteenth century pitchblende from

Jachymov came into demand as a coloring agent in ceramics and from 1898 onwards as the raw material of radium. This region was extensively mined prior to the discovery of richer deposits in the Belgian Congo and near Great Bear Lake.

Other European deposits are located at Goten, thirteen miles northeast of Sofia, the capital of Bulgaria; near Schneeberg, Saxony (from a cobalt-nickel concentrate); near Autun, Saône-et-Loire, Beauregard, Nièvre and Limoges, Haute-Vienne, in France; at Urgeirica in Portugal where pitchblende is found associated with tin and wolfram, and in Cornwall, England, where it occurs in some nickel-cobalt veins. Uraninite is found in the pegmatites of southern Norway, but has not so far assumed commercial significance.

Refineries exist at Treibach, 18 miles north of Klagenfurt in south-central Austria; at Salwick, near Preston in England, and at Oolen, Belgium. Prior to World War II most of the ores shipped from the Belgian Congo were refined at Oolen, but today there seems to be some doubt as to the amount Belgium receives from this source, as indicated by the following quotation. "The Belgian Prime Minister has denied that his country has any secret treaty forcing her to reserve Congo uranium for any particular foreign power. But only a couple of months ago Professor Cosyna, head of the nuclear physics department of Brussels University complained that respectable Belgian scientists were driven to get their uranium from the black market because the Government insisted on sending all Congo uranium straight to the United States. Some American reports suggest that Britain too has been entitled to a share of Congo uranium, but has allowed the U. S. to take up part of her allocation. Other reports say that contracts between the U. S. and the Congo mines are about to expire, and Britain is asking for an increased allocation under a new contract." (*West Africa*, August 27, 1949.)

The barite ores bearing uranium, vanadium and copper minerals in the Tyuya Muyun in the Fergana Valley, Siberia, have a limited production, while uranium in a vanadium site is found in the Karitan Range. Lake Baikal is the site of the major Russian deposit, which is rich in mendelyeevite.

Australasia. The only uranium-bearing area so far disclosed is located in the vicinity of Mount Painter, South Australia, which has minor autunite-torbernite deposits.

* * *

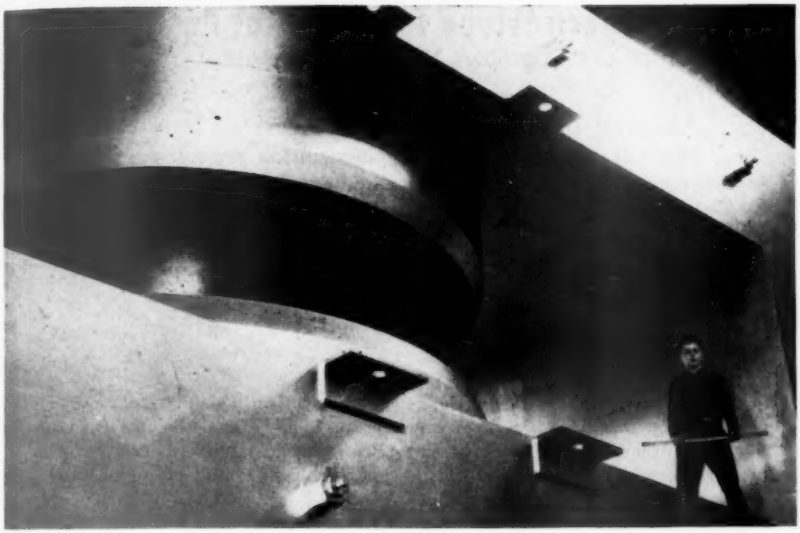
Doubtless there are many other uranium-yielding (perhaps even many other uranium-producing) areas in the world, but reliable information, even concerning their geographical distribution, is extremely hard to come by. A. F. Matthews' summary of the problem in 1946 ("Minerals Yearbook," Bureau of Mines, U. S. Dept. of the Interior, 1946) is even more apropos today. "The quantities found, mined, exported or refined (are) kept secret by all nations for security reasons and thus no measure of current or potential supply is obtainable."

Quantitative analysis of highly radioactive fission products is hindered by the necessity of limiting exposure of personnel. At Chalk River, Ontario, a Canadian National Research Council Scientist uses sensitive microchemical instruments inside hood to analyze fission products. Infinitesimal amount of radioactive substance used reduces exposure danger

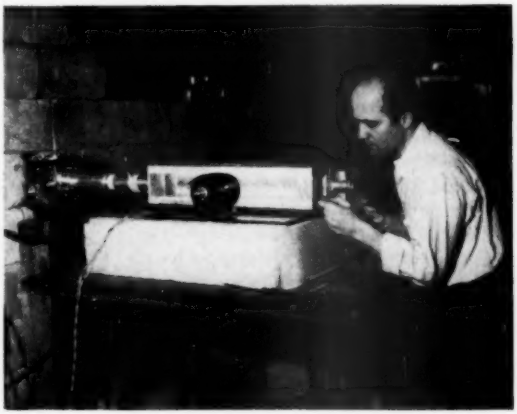
Combined with phosphors in scintillation counters, the multiplier phototube provides a convenient method of detecting and measuring radioactive particles. One such phototube is the Radio Corporation of America's 1P21. The equivalent noise input of this tube is 5×10^{-13} lumen. Worker in picture is welding components, which are then sealed in glass envelope

Tools and Methods

Addition of one-billionth of an ounce of radiobarium to oil or other solutions permits tracing of solution as it is pumped through pipe lines. California Research Corporation's chemist Don Hull is shown using a Geiger counter to check pipe-line flow. New method eliminates uncertainties of previous batch-marking systems, may point way to future economies in pipe-line operation



Expected to be in operation this year, a 400-million volt synchrocyclotron is being assembled at Carnegie Institute of Technology's Saxonburg, Pa., Nuclear Research Center. Pictured here are the 141.65-in. diameter pole tips and part of the magnet yoke. Boy holding a yardstick gives some idea of the size of the 1,465-ton magnet, whose pole tips will be surrounded by 20-ft. diameter, 87-ton copper coils. Coils will carry 20,000 amp to produce magnetic field of 20,000 gauss. Entire magnet was cast in 12 pieces



Binding energy of the last neutron in isotopes is being investigated at the University of Illinois by research assistant H. H. Palevsky. Narrow beam of electrons from 22-Mev betatron passes through evacuated tube in shield at left and enters apparatus. Isotope under study is held on two copper buttons which are rotated in beam by synchronous motor in foreground. The neutron release from specimen is detected by two BF_3 counters. (To be reported at A. P. S. meeting in Washington, April 27–29)

Neutron Spectroscopy for Chemical Analysis—III

THERMAL NEUTRONS, NEUTRON FLUX, ACTIVATION

Analytical applications of thermal neutrons are reviewed. Methods of analysis involving transmission measurements, neutron-flux reduction by an absorber, and radioactivation by neutrons are described, and their usefulness outlined.

By T. I. TAYLOR and W. W. HAVENS, Jr.

Chemistry Department *Physics Department*
Columbia University, New York, New York

IN THE FIRST PAPER (*1*) of this series, a general review was given of the properties of neutrons, the nature of their interactions, and the methods by which their interactions could be measured as a function of their velocity or wavelength. The second paper (*2*) described and illustrated the application of resonance absorption and scattering of neutrons, including transmission measurements in the $1/v$ region. The methods discussed previously require a means of measuring the transmission of samples for neutrons of known velocity or wavelength. In this, the last of the series, the uses of neutrons having a more-or-less broad energy distribution in the thermal region will be described.

Transmission Measurements with Thermal-neutron Beam

Besides reducing interferences in special cases, not much advantage is gained by using neutrons of known velocity in the thermal region. If one element in the mixture has a high cross section in this velocity region, a beam of thermal neutrons from a cyclotron or a pile can be used as described previously, except that the entire beam is used, rather than selected velocities.

The intensity of the neutrons is obtained first without the sample in the beam and then with the sample in the beam. This gives the transmission from which the concentration of the absorber can be obtained, as illustrated in the following case.

If a cyclotron, electrostatic generator, or chain-reacting pile is not available, a radium-beryllium or similar source (*3*, *4*) can be used to produce a collimated beam of thermal neutrons. See Fig. 1 on the opposite page.

Radium-beryllium sources, which usually consist of mixtures of finely divided radium chloride and beryllium metal powder sealed in a brass or monel metal container, are readily available commercially. Besides the alpha-neutron sources, photoneutron sources may also be used (*3*). It is, of course, necessary to provide adequate shielding against emitted neutrons and gamma rays if they are produced by the source.

To make an analysis with such a beam of thermal neutrons, the intensity of the beam is measured, first, without the sample in the beam (I_0) and, then, with the sample in the beam (I). This gives the transmission $T = I/I_0$. As shown in the previous articles, the numbers of atoms in the beam are related to the transmission by the equation

$$-\ln T = \sum_i n_i' \sigma_i$$

where n_i' is the number of atoms of ith kind per cm² and σ_i is the cross section of the ith atom in cm².

If the cross section and the amount of one element is such that it causes practically all of the decrease in the intensity of the neutron beam, then the effect of the other elements can be neglected, and the number of atoms of the element per cm² is given by

$$n' = -\frac{\ln T}{\sigma}$$

or

$$\mu = \frac{(-\ln T)M}{\bar{N}\sigma}$$

where μ is the grams per cm² of the element, M is its atomic weight, and $\bar{N}$ is Avogadro's number. The percentage of the element is then given by

$$\% \text{ of element} = \mu/G \times 100$$

where G is the total grams per cm² of the element and the matrix in which it occurs. The case of a binary mixture was discussed in the previous article (*2*) in which the contribution of the matrix was not neglected. A further example is given in a later section in which the contributions of all of the elements in the sample are included.

Instead of direct calculations using the known cross section of the element, it may be advantageous in many cases to prepare standards containing known concentrations of the element in a matrix similar to that of the unknown. Then, from a plot of $-\ln T$ vs μ, the value of μ for the unknown can be read. Alternatively, if the sample is the appropriate type, the addition technique can be used. When the transmission of the unknown sample has been obtained, the measurement can be repeated after adding more known amounts of the element being determined. Using the linear relationship of $-\ln T$ vs μ, one can calculate the amount of the element initially present.

Energy Distribution of Neutrons from a RaBe Source

It should be pointed out that the transmission values obtained with thermal neutron sources will depend to some extent upon the energy distribution of the particular neutron source used. For a source such as illustrated in Fig. 1, the energy distribution (*5*) is approximately as illustrated in Fig. 2. The energy distribution is such that the

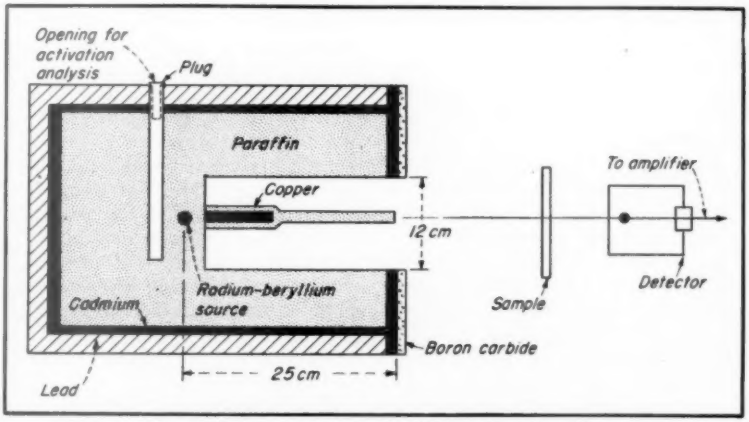


FIG. 1. Transmission measurements with a radium-beryllium source

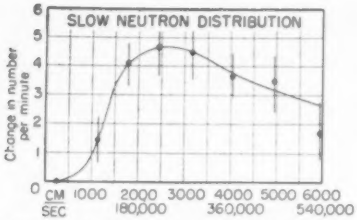


FIG. 2. Approximate energy distribution from a radium-beryllium source

cross sections for $1/v$ absorbers are effectively that for neutrons with an energy of about 0.04 ev.

Use of Cadmium Filters

For certain analyses, particularly those in which the sample contains elements that have resonance peaks near the thermal region, it may be advantageous to change the energy distribution of the beam with the appropriate filters. Cadmium filters can, for example, be used to obtain the transmission for neutrons below 0.4 ev. Since cadmium has a strong absorption resonance at 0.175 ev, a thickness of about 0.6 mm removes practically all neutrons with energies below 0.4 ev. The neutrons not transmitted by such cadmium filters are called "c" neutrons.

By making measurements with and without a cadmium filter, transmissions can be obtained for neutrons with energies above and with energies below the cadmium cut-off. Four measurements are required:

(1) Open beam intensity, I_0
(2) Intensity with the sample in the beam, I_{sample}
(3) Intensity with the cadmium filter in the beam, I_{Cd}
(4) Intensity with both the cadmium filter and the sample in the beam, $I_{Cd+sample}$

The transmission T_c for the "c" neutrons is then given by

$$T_c = \frac{(I_{sample} - I_{Cd+sample})}{(I_0 - I_{Cd})}$$

and the transmission T_{ec} for the neutrons with energies above the cadmium cut-off, *i.e.*, epi "c" neutrons, is given by

$$T_{ec} = \frac{I_{Cd+sample}}{I_{Cd}}$$

These transmission values can then be used as described above for determining the composition of the sample.

Another filtering material which has been particularly useful in neutron measurements is boron. This is because the cross section is known to be directly proportional to $E^{-1/2}$. By means of boron filters of different thicknesses, the energy distribution of the neutron beam can be changed. The thicker the boron filter, the higher the average energy of the neutron beam. In this way, the cross section of a sample for different average energy distributions may be determined.

Use of Resonance Detectors

Usually, the intensity of neutron beams is measured with a boron trifluoride counter. The radioactivation of thin foils of certain elements such as indium, gold, silver or manganese, *etc.*, can also be used (*6*). From the radioactivity induced in the foil by the (n,γ) reaction, the intensity of the neutron beam can be calculated, as described in a later section. The use of these foils is a convenient method of making transmission measurements if BF_3 counters are not available.

By placing a cadmium filter in front of one of these detector foils, thermal neutrons are removed and the foil is activated primarily by neutrons of an energy corresponding to the resonance energy of the foil element. This makes it possible to determine the transmission for a rather sharply defined energy group of neutrons. Indium, for example, has a resonance at 1.44 ev, gold at 4.8 ev, iodine at 40 ev, cobalt at 120 ev and manganese at 300 ev.

If more than one activation resonance is present in the detector, then one or

another of the levels can be discriminated against by using the proper boron or cadmium filter. Although this method has certain limitations, it can be useful in determining the transmissions at a particular energy when a velocity selector is not available. Cross sections for indium resonance neutrons have, for example, been tabulated by Marshall (*7*) and by Hanstein (*8*) and can be used for the determination of composition as described previously.

Cross Sections of Elements for Thermal Neutrons

A partial list of the elements with high cross sections in the thermal region is given in Table 1. The values are total cross sections (absorption plus scattering) for a neutron energy of 0.026 ev. They have been estimated from data reported in the literature, primarily from such compilations as the one by Way and Haines (*9*). Many of the values can be given only approximately because some of the measurements were not made precisely and because crystal diffraction effects interfered in others.

Any element that has a high cross section can be determined if it is in a matrix or on a base material that has a considerably lower cross section. Examples of systems that are under investigation are the determination of hafnium in zirconium, indium in tin, tantalum in columbium, films or electroplates of gold, silver, cadmium, rhodium, *etc.* Some of these systems are being investigated also in the resonance region (*1*, *2*). Of interest too is the use of neutron transmission to determine hydrogen dissolved in or combined with metals, hydrogen in organic compounds, or water in non-hydrogen-containing materials. The following example will illustrate the requirements of the method.

Slow Neutron Transmission

An example of an analysis by thermal neutrons is the determination of hydrogen in fluorocarbon oils (CF_2) by Burger and Rainwater (*10*) using the Columbia

TABLE 1
Approximate Cross Section of Elements for Thermal Neutrons (0.026 ev)

> 1000–100 barns		100–10 barns				10–1 barns			
Gd	36,000	Re	84	Ni	22	Mo	9.6	P	4.5
Sm	8,900	Nd	75	Pt	20	Ba	9.3	Zn	4.5
Eu	5,000	Li	66	La	18	Bi	9.1	Na	4.5
Cd	2,470	Ag	66	Pr	16	Te	9	F	4
Dy	1,200	Ho	65	Mn	15.3	As	9	Y	4
B	718	Yb	60	Fe	13.5	Ru	9	Mg	3.8
Ir	450	H	(60–30)	Tl	13	Sb	8.8	O	3.7
Hg	440	Cl	55	Rb	12.6	Zr	8	Ca	3
Er	200	Cs	50	V	12	Cb	7.5	Ne	2.8
In	196	Tb	44	N	12	Cr	6.5	Si	1.8
Rh	155	Co	41	Br	11.5	Be	6.1	Al	1.6
Tm	120	Xe	37	Sr	11	Ga	6	A	1.5
Lu	115	Os	31	Pb	11	Ce	6	He	1.5
Hf	110	Se	28	Ti	11	C	4.8	S	1.4
Au	104	Kr	27	Ge	10.8	Sn	4.8		
		Ta	25	Pd	10.5				
		W	23	I	10				
		Sc	22	Cu	10				

University cyclotron. Measurements were made with an empty cell, the unknown sample, and a standard sample of nearly the same composition as the unknown. Then, from the transmission measurements and the weight per cm², the per cent of fluorine atoms replaced by H atoms relative to a standard could be calculated, as illustrated in the following example.

If there are n' (CF_2) units per cm² of a pure fluorocarbon in a sample and one assumes the cross sections of carbon and fluorine to be 4.8 and 4 barns, respectively, the transmission is given by

$$-\ln T = n'(\sigma_C + 2\sigma_F) = n' \times 12.8 \times 10^{-24}.$$

If the mass per cm² is μ and the molecular weight is 50, the number of atoms per cm², $n' = \mu \times (6.02 \times 10^{23})/50$. Substitutions for the n' in the above equation gives:

$$\frac{-\ln T}{\mu} = \frac{12.8 \times 10^{-24} \times 6.02 \times 10^{23}}{50} = 0.154.$$

If a fraction x of the fluorine atoms in fluorocarbon (CF_2)x are replaced by hydrogen atoms, then

$$-\ln T = n'[\sigma_C + 2(1-x)\sigma_F + 2x\sigma_H] \cong n'[4.8 + 8 - 8x + 60x] \times 10^{-24} \cong n'[12.8 + 52x] \times 10^{-24}$$

The number of atoms per sq cm is:

$$n' = \frac{\mu \times 6.02 \times 10^{23}}{50 - 38x + 2x}$$

Substitution gives:

$$\frac{-\ln T}{\mu} = 0.602\left[\frac{12.8 + 52x}{50 - 36x}\right] \cong 0.154(1 + 4.8x)$$

That is, the value of the total cross section increases by $4.8x$ when a fraction x of the fluorine atoms are replaced by hydrogen atoms, provided the grams per square centimeter remain the same.

From the ratio of the effective cross sections per unit weight per cm² of the sample as compared to the standard, the fraction x of hydrogen atoms replacing fluorine atoms can be solved from:

$$\left[\frac{\left(\frac{-\ln T}{\mu}\right)_{\text{sample}}}{\left(\frac{-\ln T}{\mu}\right)_{\text{standard}}} - 1\right] = 4.8x$$

Using samples of about 10 grams per cm² determined to within 0.2–0.3% and counting times sufficient to give 40,000 counts, one can determine the ratio of the transmissions to within about 1% uncertainty. This corresponds to about 2 parts per 1,000 in the uncertainty in the replacement of F by H. In a typical case, for example, the value of $(-\ln T/\mu)$ for the standard was 0.1413, while that for the sample was 0.1480.

Hence, from the equation above, $0.0475 = 4.8x$, and $x = 0.0099$ or 9.9 fluorine atoms per 1,000 replaced by hydrogen atoms.

The percentage of water or hydrogen in metals or in inorganic or organic compounds can be determined in a similar manner. If one wants to find out how much hydrogen there is in a sample of iron, the transmission can be determined. Then, by heating and evacuation, the hydrogen can be removed and the transmission redetermined.

If, for example, the transmission of the iron sample containing the bound hydrogen is T and the transmission after removal of the hydrogen is T', then

$$-\ln T = n'_{Fe}\sigma_{Fe} + n'_H\sigma_H$$
$$-\ln T' = n'_{Fe}\sigma_{Fe}$$

Subtracting,

$$\ln (T'/T) = n'_H\sigma_H$$

Assume that the transmission increased from 10.0% to 10.5% when the hydrogen was removed, an easily measurable change; then

$$n'_H = \frac{0.049}{60 \times 10^{-24}} = 8.2 \times 10^{20}$$

atoms per cm².

This is $(8.2 \times 10^{20})/(6.02 \times 10^{23}) = 1.35 \times 10^{-3}$ moles per cm² or 1.36 mg of H per cm².

The weight of iron required to give a transmission of 10.5% is

$$n'_{Fe} = \frac{-\ln T}{\sigma_{Fe}} = \frac{2.25}{13 \times 10^{-24}}$$

$= 1.73 \times 10^{23}$ atoms per cm^2 or $(1.73 \times 10^{23})/(6.02 \times 10^{23}) = 0.287$ moles per cm^2. This is 16.0 grams per cm^2, or a piece about 2.1 cm thick. The percentage by weight of hydrogen in such a sample would be $0.00136 \times 100/16.0 = 0.0085\%$ H by weight. Thus, it can be seen that the method is reasonably sensitive, but the size of sample required for low percentages of hydrogen is rather large.

To determine hydrogen in organic compounds, the compound can be dissolved in carbon disulfide, a fluorocarbon, or other solvent that does not contain hydrogen. The intensity I of the neutron beam with the solvent plus sample divided by the intensity I_0 of the beam with the solvent alone gives the transmission of the sample. About 45 mg per cm^2 of hydrogen would be required to give a transmission of 20% which, if determined to 1%, would give the hydrogen content of the compound to within about 5 parts in 1,000.

Absorption of Thermal Neutrons

By their effect on the flux of thermal neutrons, elements or isotopes with high absorption cross sections can be determined when in a matrix of other substances of low absorption cross section. This has been done by measuring the effect of a sample containing the element in the flux of neutrons near a radium-beryllium source, or in a chain-reacting pile.

For example, a laboratory procedure has been devised (*11*) for determining boron in boron carbide with a 1 gram RaBe source. In this method, the sample is dissolved or reduced to a very fine state of subdivision (below 325 mesh, preferably 600 mesh) to reduce the extent of self-absorption in single grains of the material. The sample is then placed in a container equipped with a neutron detector, as illustrated schematically in Fig. 3.

The counting rate is determined with the sample uniformly dispersed throughout the fixed volume of water. A sufficient amount of sample is used to reduce the counting rate to about one-

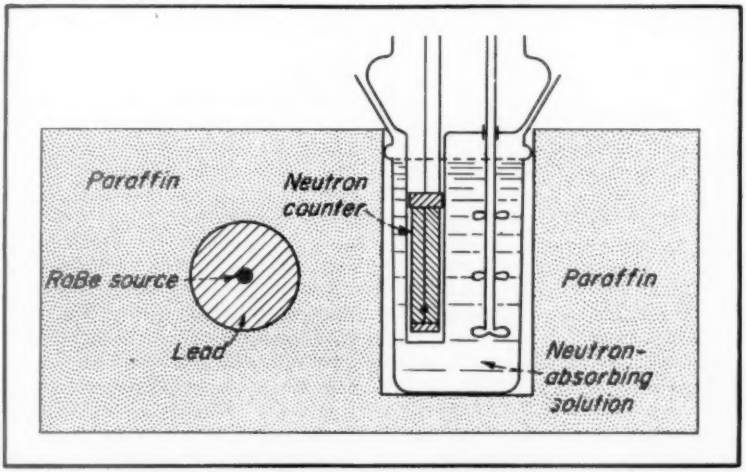


FIG. 3. Schematic arrangement for analysis by absorption of thermal neutrons

third the value for pure water. Next, the substance sought is added in known quantities to the fixed volume of water, or similar matrix, until the same absorption of neutrons is obtained. It is assumed, then, that the same weight of the absorbing element is present in both cases. From this information, the per cent of the element or isotope in the sample can be estimated. It was possible, for example, to determine from a 3- to 4-gram sample of boron carbide that it contained 59.5% B.

Pile Reactivity Method

The methods used for determining the absorption cross sections of elements in the chain-reacting pile can be used for analysis once the cross sections have been determined or alternatively direct comparisons have been made between the effect of the sample and the effect of suitable standards. One method is based on the fact that the introduction of a neutron-absorbing substance in a pile decreases the reactivity of the pile (*12*). To keep the power level constant, the control rods must be withdrawn a certain distance. By proper calibration with standards, a determination can be made of the weight of absorber in the sample, provided unknown interfering substances are not present.

Pile Oscillator Method

The pile oscillator may also be applied to analysis in special situations (*13*), although its primary use is to measure absorption cross sections. Here, a sample containing a substance of high absorption cross section is passed back and forth close to a neutron counter suitably placed in the graphite of the pile.

The oscillation of the sample produces uniform fluctuations in the ion current of the detector due to local depressions in the neutron flux as the sample passes the detector. Alternatively, the sample is passed in and out of the pile to produce a fluctuation in the power of the pile. Suitable amplifier and integrator circuits measure the magnitude of the effect.

A comparison of the effect for the sample with the appropriate standards would enable the estimation of the per cent of the absorber in the sample.

Slow Neutron Activation

Inasmuch as analysis by slow neutron activation has been recently reviewed (*14*), only a brief discussion will be given here. The sample to be analyzed is placed in a flux f of neutrons for a time sufficient to produce a measurable activity as a result of absorption of neutrons by the element sought. The rate of growth of radioactive atoms N^* is given by the difference between the rate of formation of active atoms and their rate of decay:

$$dN^*/dt = f\sigma_{ac}N - \lambda N^*$$

Integration for the time of irradiation gives the equation

$$N^* = \frac{f\sigma_{ac}N}{\lambda}(1 - e^{-\lambda t_1})$$

from which the activity is

$$A_{t_1} = N^*\lambda = f\sigma_{ac}N(1 - e^{-\lambda t_1})$$
$$= f\sigma_{ac}N(1 - e^{-0.693t_1/T_{1/2}})$$

where f is neutron flux in neutrons per sq cm per sec; σ_{ac} is the cross section for the absorption of neutrons in sq cm per atom for the natural element; N is the number of target atoms; and λ is the decay constant for the radioactive isotope which may be expressed in terms of its half-life $T_{1/2}$ by $\lambda = 0.693\ T_{1/2}$. A_t is the activity in disintegrations per second at the time t_1, when the neutron irradiation is stopped. These equations show that irradiation for a period of time equal to several half-lives gives practically the maximum activity obtainable ($f\sigma_{ac}N$) and that irradiation for a period of time equal to a half-life gives one-half the maximum value.

If the activity is measured at a time t_2 after the irradiation was stopped, the

disintegrations per second A_{t_2} will be given by:

$$A_{t_2} = A_{t_1} e^{-\lambda t_2}$$

or, combining with the above equations,

$$A_{t_2} = f\sigma_{ac} N (1 - e^{-0.693 t_1 / T_{1/2}}) \times (e^{-0.693 t_2 / T_{1/2}})$$

The number of atoms N of an element in a sample of weight g, is

$$N = 6.02 \times 10^{23} \times g/M$$

where M is the atomic weight. Substituting for N and then solving for g, weight of the element in the sample is:

$$g = \frac{A_{t_2} M}{6.02 \times 10^{23} f \sigma_{ac} (1 - e^{-0.693 t_1 / T_{1/2}}) \times (e^{-0.693 t_2 / T_{1/2}})}$$

To calculate the weight of the element in the sample, it is necessary to know the neutron flux, the cross section for activation, and the half-life. In addition, the number of disintegrations per second must be determined rather precisely. This is not easy to do because the actual count observed with the Geiger-Müller counter, for example, must be corrected for the following: counter efficiency for the radiations; geometry (fraction of the solid angle effective in the counting); absorption of radiations by the walls, air, and the sample itself; forward scattering from the sample or surroundings; and back-scattering from the sample mount, *etc.* All of these factors tend to affect the net *counting* yield which, for most cases, falls between 5 and 35%.

As a result, it is difficult to determine precisely the weight of the element from counting on a single unknown sample. Orders of magnitude or limiting concentrations are, however, frequently of interest. For example, a measured count of 2,200 per minute for manganese ($\sigma_{ac} = 12$) taken directly after a saturation irradiation in a flux of 10^9 neutrons per second would, assuming a counting yield of 25%, indicate the presence of approximately 1 μg of Mn in the sample.

More precise determinations can be made by comparing the unknown sample with standards of similar composition. The unknown and standard are irradiated, and then counted, under as nearly identical conditions as possible. The weight of the element x in the unknown is then given by:

$$\frac{\text{weight of } x \text{ in unknown}}{\text{weight of } x \text{ in standard}} = \frac{\text{activity from } x \text{ in unknown}}{\text{activity from } x \text{ in standard}}$$

If chemical operations are necessary to remove bulk constituents or interfering radioactive elements, then both standard and unknown are treated in the same way. The element of interest is finally isolated, and its activity is determined and compared with the standard. To be certain of the radiochemical purity of the isolated element, it is advisable to determine its half-life and its aluminum or lead absorption curve. The resolution of the decay curve and the characterization of the radiations may also give valuable qualitative information about the presence of other elements. In fact, it may be desirable to run such a preliminary qualitative analysis on a sample before making the chemical separations.

When the element to be determined is present in trace amounts, a small known amount of the naturally occurring element is added *after* irradiation. This serves as a "carrier" to aid in the separation and isolation of the element. It also serves as a means of determining the "chemical yield" of the processes. The observed counting rates for the standard and unknown samples can then be corrected for chemical losses. In addition, corrections for self-absorption may be needed if the weights of the compounds counted are appreciably different for standard and unknown.

The principal source of uncertainty in such determination by the comparison method is the uncertainty in the counting rate. It is estimated that trace constituents can be determined with an accuracy of $\pm 10\%$ which, for

TABLE 2
Sensitivities Using Different Neutron Sources

Neutron Source	*Usable neutron flux* ($n/cm^2/sec$)	*Approximate weight to give 100 counts per min* $\sigma_{ac} = 10$ barns
Pile	10^{10} to 10^{12}	1×10^{-8} to 1×10^{-10} gm
Cyclotron	10^{8} to 10^{9}	1×10^{-6} to 1×10^{-7} gm
Low-Voltage D-D Neutron Generator	10^{5} to 10^{6}	1×10^{-3} to 1×10^{-4} gm
1 gm RaBe	10^{4} to 10^{5}	1×10^{-2} to 1×10^{-3} gm
1 curie SbBe 60-d half-life	10^{3} to 10^{4}	1×10^{-1} to 1×10^{-2} gm
1 curie PoBe 140-d half-life	10^{3} to 10^{4}	1×10^{-1} to 1×10^{-2} gm

trace and impurity analysis, is frequently sufficient.

Sensitivity of Activation Method

From the equations in the previous section, it can be seen that the factors contributing to the sensitivity of the method are: neutron flux, f; activation cross section, σ_{ac}; and the half-life, $T_{1/2}$. The nature of the radiation is also important because it, as well as other factors, affects the net counting yield. The chain-reacting pile gives the most intense source of neutrons, from 10^{10} to 10^{12} neutrons per cm^2 per sec. Cyclotrons with a 100-μa beam of 10-Mev deuterons on a beryllium target can produce as high as 10^{12} neutrons per sec, or a flux of from 10^{8} to 10^{9} neutrons per cm^2 per sec at distances of from 10 to 20 cm from the target.

A one-gram RaBe source (*15*) produces about 10^{7} neutrons per second or a flux of about 10^{4} to 10^{5} neutrons per cm^2 per sec at 8 to 10 cm. Similar neutron fluxes can be obtained from other α-n sources such as PoBe or RnBe (*3*).

Photoneutron sources such as those with 87-day Y or 60-day Sb are also useful (*16*).

Low-voltage neutron generators, in which several hundred microamperes of 200-kev deuterons bombard heavy-water ice, or deutero-paraffins, can produce intensities up to 10^{7} or 10^{8} neutrons per sec (*17*) and, consequently, can produce fluxes somewhat higher than the usual RaBe source.

A summary of the effectiveness of the different sources in detecting elements with activation cross sections of about 10 barns is given in Table 2. These values are calculated on the basis of the neutron fluxes given and 100 counts per minute at a 25% counting yield for an element with atomic weight 100 when given a saturation exposure to the neutron flux.

The results tabulated in Table 2 show that, for elements with cross sections as high as 10 barns and with neutron fluxes as high as 10^{12} neutrons per cm^2 per sec, phenomenal sensitivity may be achieved, 10^{-10} gm being detectable in such cases. For low neutron fluxes, however, the method is not too sensitive. Special applications may be found even here if the element in question has a reasonably high cross section, and high sensitivity is not required. This may be true for certain alloys or ores.

Activation Cross Sections

For the radioactivation method to be applicable, not only must the activation cross section be large enough, but the

TABLE 3 **Thermal Neutron Activation Cross Sections and Properties of the Radioisotopes Produced** (*9, 14, 18, 19, 20.*)*

Element	*Atomic Activation Cross Section*	*Half-life*	*Radioactive Isotope*	*Energy of Radiation*
Dy	805	1.25m	Dy^{165}	*I.T.* 0.18; e^- 0.13
	749	2.4h	Dy^{165}	β^- 0.42, 0.88, 1.25; γ 0.78, 0.37, 0.091
Eu	678	9.2h	Eu^{152}	β^- 1.88; γ 0.725, 0.163, 0.123
Ir	285	70d	Ir^{192}	β^- 0.67; γ 0.137, 0.208, 0.296, 0.308, 0.317, 0.469, 0.488, 0.592, 0.607
	100	1.5m	Ir^{192}	γ 0.06; e^- 0.047, 0.038
	78.8	19h	Ir^{194}	β^- 2.2, 0.48; γ 1.4, 0.3
In	139	54m	In^{116}	β^- 0.85; γ 2.32, 1.31, 1.12, 0.428
	49.8	13s	In^{116}	β^- 2.8; γ none
	2.4	48d	In^{114}	e^- 0.162, 0.187; *I.T.* 0.192
Rh	137	43s	Rh^{104}	β^- 2.6; γ 0.4
	11.6	4.3m	Rh^{104}	γ 0.08; e^- 0.069
Tm	106	127d	Tm^{170}	β^- 0.98; γ 0.83 (?)
Au	96.4	2.7d	Au^{198}	β^- 0.96; γ 0.4112; e^- 0.330
Lu	91	6.7d	Lu^{177}	β^- 0.47; γ 0.2
	15.9	3.4h	Lu^{176}	β^- 1.15; γ none
Ho	59.6	27.5h	Ho^{166}	β^- 1.8
Sm	53	47h	Sm^{153}	β^- 0.78; γ 0.10, 0.61, 0.062
	1.1	25m	Sm^{155}	β^- 1.9; $\gamma \sim 0.3$
Ag	48	24.2s	Ag^{110}	β^- 2.8; γ (?)
	23	2.3m	Ag^{108}	β^- 2.8
	1.1	225d	Ag^{110}	$\beta^- < 0.1, 0.59$; γ 0.90 (47%), 0.66 (44%), 1.40 (9%)
Re	47.1	18.9h	Re^{188}	β^- 2.05, 0.225; γ 0.16, 0.64, 0.94, 0.48, 1.43
	37.4	92.8h	Re^{186}	β^- 1.07; γ none
Cl	40	2×10^6y	Cl^{36}	β^- 0.66; β^+
	0.14	38m	Cl^{38}	β^- 4.94 (53%), 1.19 (36%), 2.79 (11%); γ 2.15 (57%), 1.60 (43%)
Cs	25.6	2.3y	Cs^{134}	β^- 0.658 (75%), 0.09 (25%) γ 0.602, 0.794, 0.568, 1.396
	0.016	3.1h	Cs^{134}	β^- 2.4; γ 0.7; *I.T.* 0.16
Tb	>22	77d	Tb^{160}	β^- 0.88, 0.546; γ 0.086, 0.195, 0.213, 0.298, 1.15
	11	3.9h	Tb^{160}	β^- (?)
Co	22	5.3y	Co^{60}	β^- 0.308; γ 1.115, 1.317
	0.66	10.7m	Co^{60}	β^- 1.35; γ 1.5; e^- 0.048
Sc	22	85d	Sc^{46}	β^- 0.36, 1.49; γ 0.89, 1.12
Ta	20.6	117d	Ta^{182}	β^- 0.525; γ 1.22 (57%), 1.13 (37%)
	0.034	16.2m	Ta^{182}	β^- 0.4 or 0.2
Yb	15	99h	Yb^{175}	β^- 0.13, 0.50; γ 0.35
	~15	33d	Yb^{169}	γ 0.2, 0.4
	0.8	~2.5h	Yb^{177}	β^- 1.2
Mn	10.7	2.59h	Mn^{56}	β^- 2.81 (50%), 1.04 (30%), 0.75 (20%) γ 0.822 (100%), 1.7 (30%), 2.06 (20%)

(*Continued on next page*)

Table arranged in order of decreasing cross section.

Underscored mass numbers indicate metastable nuclear isomers.

? Indicates uncertainty
β^- Negative beta particles
β^+ Positive beta particles
γ Gamma rays
α Alpha particles
e^- Internal conversion electrons
I.T. Isomeric transition
X X-rays
* Taken largely from references listed

TABLE 3—(*Continued*)

Element	*Atomic Activation Cross Section*	*Half-life*	*Radioactive Isotope*	*Energy of Radiation*
Pr	10.1	19.3h	Pr^{142}	β^- 2.14, 0.21; γ 1.9, 0.134, 0.329, 0.490, 0.624
W	10	24.1h	W^{187}	β^- 0.63 (70%), 1.33 (30%); γ 0.48, 0.21, 0.69, 0.62, 0.138, 0.078
	0.64	73.2d	W^{185}	β^- 0.43; γ none
La	8.4	40h	La^{140}	β^- 1.4 (70%), 0.90 (20%), 2.12 (10%); γ 1.64, 0.85, 0.49, 2.4, 0.335
I	6.25	24.99m	I^{126}	β^- 2.02 (93%), 1.59 (7%); γ 0.428 (7%)
Hg	4.8	64h and 23h	Hg^{197} Hg^{197}	γ 0.077 γ 0.165, 0.135, 0.250, 0.077
	0.72	51.5d	Hg^{203}	β^- 0.205; γ 0.286
	0.023	5.5m	Hg^{205}	β^- 1.62
V	4.5	3.7m	V^{52}	β^- 2.7; γ 1.44
As	4.2	26.8h	As^{76}	β^- 3.04 (60%), 2.49 (25%), 1.29 (15%) γ 0.55 (79~%), 1.20 (~30%)
Br	4.1	18m	Br^{80}	β^- 2.0; γ <0.5
	1.4	4.4h	Br^{80}	γ 0.037, 0.049
	1.12	34h	Br^{82}	β^- 0.465; γ 0.547, 0.787, 1.35
Sb	3.9	2.8d	Sb^{122}	β^- 1.36, 1.94; γ 0.57
	1.1	60d	Sb^{124}	β^- 0.68, 2.37, 0.48, 1.0, 1.6 γ 0.603, 1.70, 0.71, 0.65, 2.06
Hf	3.5	46d	Hf^{181}	β^- 0.460; γ 0.342, 0.128, 0.472
	(?)	19s	Hf^{179}(?)	*I.T.*; e^- 0.19
Pd	3.0	13.4h	Pd^{109}	β^- 1.1; γ none
	0.053	26m	Pd^{111}	β^- 3.5
Ni	2.9	16y	Ni^{59}	β^- ~0.05
	0.54	300y	Ni^{63}	β^- 0.05
	0.030	2.6h	Ni^{65}	β^- 1.9; γ 1.1
Os	2.2	32h	Os^{191}	β^- 1.2; γ 1.17, 1.58
	0.66	15d	Os^{193}	β^- 0.142; γ 0.129, 0.039
Cd	0.29	2.33d	Cd^{115}	β^- 1.13, 0.6; γ 0.52
	0.2	48.7m	Cd^{115}	γ 0.247
	0.10	2.8h	Cd^{117}	β^- 1.3–1.7
	0.051	2.3m	Cd^{113}	(?)
	0.040	44d	Cd^{115}	β^- 1.7; γ 0.5
	~0.01	6.7h	Cd^{107}	γ 0.846; β^+ 0.32
Nd	0.26	11.0d	Nd^{147}	β^- 0.90 (60%), 0.4 (40%); γ 0.58 (40%)
	0.14	1.7h	Nd^{149}	β^- 1.5; γ or X
Zn	0.25	250d	Zn^{65}	γ 1.11 (46%); β^+ 0.35
	0.2	57m	Zn^{69}	β^- 1.0; γ none
	0.054	13.8h	Zn^{69}	γ 0.44
	0.0005	2.2m	Zn^{71}	β^- 2.1; γ
Se	0.24	18m	Se^{81}	β^- 1.5; γ none
	0.017	58m	Se^{81}	γ 0.099
	0.005	25m	Se^{83}	β^- 1.5; γ 0.17, 0.37, 1.1
	0.004	67s	Se^{83}	β^- 3.4; γ
P	0.23	14.3d	P^{32}	β^- 1.712; γ none
Al	0.21	2.4m	Al^{28}	β^- 3.01; γ 1.80
Te	0.15	9.3h	Te^{127}	β^- 0.70; γ none
	0.076	25m	Te^{131}	β^-
	0.0435	71m	Te^{129}	β^- 1.8; γ 0.3, 0.8
	0.014	90d	Te^{127}	γ 0.086
	0.0051	32d	Te^{129}	γ 0.102
	>0.003	30h	Te^{131}	
Fe	0.15	~4y	Fe^{55}	γ 0.07 (?)
	0.0017	47d	Fe^{59}	β^- 0.26, 0.46; γ 1.10, 1.30
Ge	0.14	89m	Ge^{75}	β^- 1.2
	0.09	11.4d	Ge^{71}	γ 0.32, 0.6 (?)
	<0.015	39.6h	Ge^{71}(?)	β^+ 1.2
	0.0073	59s	Ge^{77}	β^- 2.8
	0.0065	12h	Ge^{77}	β^- 2.0; γ
Sr	0.13	2.7h	Sr^{87}	γ 0.386
	0.004	54d	Sr^{89}	β^- 1.5; γ none
Ce	0.12	33h	Ce^{143}	β^- 1.35; γ 0.5
	>0.4	30d	Ce^{141}	β^- 0.55; γ 0.21
Mo	0.19	67h	Mo^{99}	β^- 1.05, 0.21; γ 0.75 (80%),

Tl	2.2	3.5y	Tl^{204}	β^- 0.87; γ none
	0.078	4.23m	Tl^{206}	β^- 1.7; γ none
Cu	1.99	12.8h	Cu^{64}	β^- 0.571; γ 1.35 (3.5 %)
	0.56	5m	Cu^{66}	β^- 2.0; γ 1.32
Ga	1.3	14.1h	Ga^{72}	β^- 0.56, 0.74, 1.00, 1.45, 1.74, 2.57, 3.17 γ 0.84, 0.63, 2.2, 2.5, 1.05, 1.81, 1.6
	0.8	20m	Ga^{70}	β^- 1.65; γ
Y	1.2	64h	Y^{90}	β^- 2.35; γ none
Cb	1.2	6.6m	Cb^{94}	β^- 1.35 ($\sim$0.1 %); γ 1.0
Pt	1.14	3.3d	Pt^{197}	β^- (?); γ (?)
	0.28	31m	Pt^{199}	β^- 1.8
	0.28	18h	Pt^{197}	β^- 0.7
Er	> 1.0	7.5h	Er^{171}	β^- 1.05 (71 %), 0.67 (22 %), 1.49 (6 %); γ 0.305 (71 %), 0.113 (71 %), 0.81 (22 %)
	> 0.06	20b	Er^{171}	β^- 0.6; γ
Sn	1.0	105d	Sn^{118}	γ 0.085; ϵ^- 0.055, 0.080
	0.083	28h	Sn^{121}	β^- 0.4; γ none
	0.035	9m	Sn^{125}	β^- $\sim$ 2.2; γ $\sim$ 0.74
	0.018	$\sim$400d	$Sn^{<126}$	(?)
	0.008	10d	Sn^{123}	β^- 2.6
Gd	$\sim$0.94	19h	Gd^{161}	β^- 0.85; γ 0.3
	0.6	8.6d	Gd(?)	
	< 0.25	75d(?)	Gd^{153}	γ 0.102
Na	0.63	14.8h	Na^{24}	β^- 1.39; γ 1.38, 2.76
A	0.62	109m	A^{41}	β^- 1.18, 2.55 (0.7 %); γ 1.37
Rb	0.52	19.5d	Rb^{86}	β^- 1.82, 0.72; γ 1.081
	0.033	17.5m	Rb^{88}	β^- 4.6
Cr	0.494	26.5d	Cr^{51}	γ 0.32; ϵ^- 0.2
	0.00014	7.3h(?)	Cr^{55}	β^- 1.4
Ru	0.38	42d	Ru^{103}	β^- 0.665 (5 %), 0.350 (95 %); γ 0.55
	0.12	4.5h	Ru^{105}	β^- 1.35; γ 0.76
	0.0006	2.8d	Ru^{97}	γ 0.23
Ba	0.37	85m	Ba^{139}	β^- 2.27; γ 0.163
	0.006	> 20y	Ba^{133}	γ 0.32, 0.085
Mo	0.10	67h	Mo^{99}	β^- 1.05, 0.21; γ 0.75 (80 %), 0.24 (20 %)
	0.05	14.6m	Mo^{101}	β^- 1.0, 2.2; γ 0.3, 0.9
Zr	0.075	65d	Zr^{95}	β^- 0.394 (98 %), 1.0 (2 %); γ 0.73 (93 %), 0.92 (7 %), [0.23 (93 %)]
	0.017	17.0h	Zr^{97}	β^- 2.1; γ $\sim$0.8
K	0.067	12.44h	K^{42}	β^- 3.58 (75 %), 2.04 (25 %); γ 1.51
Kr	0.055	4.5h	Kr^{85}	β^- 0.94; γ 0.17, 0.37
	0.036	$\sim$10y	Kr^{85}	β^- 0.74; γ none
	0.011	74m	Kr^{87}	β^- 4
	0.00089	34h	Kr^{79}	β^- $\sim$0.9 (30 %), $\sim$0.6 (70 %); γ 0.2
Xe	0.05	5.3d	Xe^{133}	β^- 0.35; γ 0.085; ϵ^- 0.049; X 0.031
	0.02	9.2h and 13.0m	Xe^{135}	β^- 0.94; γ 0.25 γ 0.53; ϵ^-0.50
	0.013	3.9m	Xe^{137}	β^- $\sim$ 4
Li	0.031	0.88s	Li^8	β^- 12.7, 15.8; γ none
Bi	0.015	5.0d	Bi^{210}	β^- 1.17; γ none; α 4.87
Ca	0.013	152d	Ca^{45}	β^- 0.260; γ none
	0.001	30m	Ca^{49}	β^-
	0.0004	2.5h	Ca^{49}	β^- 2.3; γ 0.8
	0.0002	10d	Ca^{41}	
S	0.011	87.1d	S^{35}	β^- 0.169
	0.000022	5.04m	S^{37}	β^- 1.6 (90 %), 4.3 (10 %); γ 2.7
Be	0.01	2.7×10^6y	Be^{10}	β^- 0.65, 0.56(?); γ none
F	0.0094	12s	F^{20}	β^- 5.0; γ 2.2
Mg	0.0054	10.2m	Mg^{27}	β^- 1.78 (80 %), 0.79 (20 %); γ 1.02, 0.84, 0.64
Si	0.0048	170m	Si^{31}	β^- 1.8; γ none
Ti	0.0021	72d	Ti^{51}	β^- 0.45; γ 1.02
	0.0075	6m	$Ti^{?}$	β^- 1.6; γ
C	0.0011	5400y	C^{14}	β^- 0.156; γ none
Pb	0.00024	3.32h	Pb^{209}	β^- 0.68; γ none
O	4.5×10^{-7}	27s	O^{19}	β^- 2.0, 4.5; γ 1.6
N	0.8×10^{-7}	7.35s	N^{16}	β^- 3.8, 4.3, 10.3, 5.2; γ 6.2, 6.7
H	0.6×10^{-7}	12.1y	H^3	β^- 0.0179; γ none

nature of the radiation emitted from the isotope must be favorable for measurement. Table 3 lists the elements in the approximate order of their decreasing cross section. The values have been taken from a number of available sources and no attempt has been made to evaluate the reliability of the data.

For practical application, it is desirable that the half-life be not less than several minutes and not longer than two or three days. The cross section required depends upon the sensitivity needed and the neutron flux available. With the pile, where high neutron fluxes are available, 50 to 75 of the stable elements have properties that are more or less suitable for determination by this method. A number of the lighter elements and those that have very low cross sections, or a very short half-life for the radioisotope produced, cannot conveniently be determined by radioactivation with neutrons.

In addition to analysis of the elements, the radioactivation method may also be used for determination of the abundance of isotopes. For example, the isotopic composition of copper can be determined by comparison of the 12.8-h Cu^{64} and the 5-m Cu^{66} activities induced in a standard of known isotopic abundance and in the unknown.

Of course, the radioactivation method of analysis is not limited to the use of neutrons. Charged particles from cyclotrons or electrostatic generators can be used in many cases. Bombardment of iron with 6.4-Mev deuterons was used by Seaborg and Livingood (*21*), for example, to determine the presence of about 6 parts per million of gallium. The determination of copper in silver (*22*), sodium in aluminum (*23*), and carbon in steel (*24*), are all examples of radioactivation by particles other than neutrons.

* * *

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The Relativistic Mass-Energy Relationship — Has It Been Verified Accurately?

By S. W. FLÜGGE

*Institut für Struktur der Materie, Universität, Marburg, Germany**

THE RELATIVISTIC equivalence principle of mass and energy is one of the most fundamental and powerful laws in theoretical physics.

As this principle met the general development of physics, the idea of matter began to dissolve into that of field, the material particles simply meaning singularities of the force fields which they originated, and their masses, the most significant property of matter, slowly changing into the self-energies of such fields. The calculation of this self-energy from the field has met insurmountable difficulties, which fact shows that the idea of field-singularities has not yet been completely understood; but, in principle, there can be no doubt that the electron mass has to be considered as self-energy of the electromagnetic field, and the nucleon mass as self-energy of the nuclear field.

Evidence was so readily available to substantiate the many new ideas derived from the equivalence principle that there was no need of experimental proof by real conversion of mass and energy into one another. From the time the theory of relativity was first made known, however, some experimental evidence existed for parallelism between the velocity dependences of mass and energy, first deduced by Einstein, and the experimental cornerstone of our principle of special relativity. But a true transmutation of mass into energy, or of energy into mass, was not achieved for another score of years. It seemed very unlikely, in fact, in the early days, to perform any such transmutation at all because, from the relation

$$E = Mc^2,$$

it follows that a gigantic amount of energy will correspond to only a very modest mass.

Mass Defect

A certain chance to find some such transmutation in nature is contained in the physical concept of *mass defect*: The entire mass of a physical system composed of several particles linked together by attractional forces will be

*Present address: Department of Physics, University of Wisconsin, Madison, Wisconsin.

Although seemingly revolutionary, the theorem suggesting that mass is nothing but a peculiar form of energy underwent remarkable development during the years after its discovery. But now it appears that direct measurements of the equivalence between mass and energy are quite inaccurate and that, in evaluating the quantitative validity of the relativistic equivalence principle, certain check methods ought to be considered.

less than the mass of these particles if separated from each other by an amount

$$\Delta M = \Delta E/c^2,$$

if ΔE is the binding energy of the system. If the theory of relativity is right, this relation must hold for *any* physical system.

If one tries to apply this principle to chemical binding, or even to the binding of electrons in an atom, one finds that the mass defects to be expected are not larger than a fraction of about 10^{-8} or 10^{-9}, which is by far too small to be discovered by experiment.

The first qualitative support was not found until work on atomic nuclei started in the early twenties. Even though the order of magnitude of the mass defects reaches the order of nearly 1% with atomic nuclei, the situation, in most cases, is not very favorable. It is usually impossible to measure the *whole* binding energy of a nucleus if it undergoes a transmutation into one of its neighbors in the Periodic Table during a nuclear reaction. (Only the *changes* in binding energy can be measured.) The order of magnitude, therefore, is only about 10^{-4} of the mass of the nucleus, but even this small amount is large enough to allow measurements of sufficient accuracy by help of the very refined mass-spectroscopic technique.

On the other hand, energy changes can be calculated from the kinetic energies of incoming and outgoing particles. Using the energy scale most appropriate for such experiments with 1 Mev as energy unit (1 Mev = 1.601×10^{-6} ergs) and measuring masses in "milli mass units" (mmu), *i.e.*, in thousandths of the mass unit of the atomic-weight scale (1 mmu = 1.6600×10^{-27} gm), one can reason that the equivalence principle leads to a conversion factor between mass and energy of

$$1 \text{ mmu} = 0.931 \text{ Mev}.$$

Then, every experimental check of this conversion factor will also be a check of the quantitative validity of the relativistic equivalence principle.

Let us consider a simple example of this check method. The energy liberation of the nuclear reaction $N^{14}(d,p)N^{15}$ is measured by the kinetic energies of the incident deuteron and the outgoing proton, provided that the remaining kinetic energy of the N^{15} nucleus can be calculated from the law of momentum conservation. This energy liberation amounts to (8.55 ± 0.08) Mev (*1*). Ewald (*2*) in 1946 remeasured the mass-spectroscopic doublet $N^{14}H—N^{15}$ and found $(107.76 \pm 0.20) \times 10^{-4}$ mu, and the mass difference $H_2—D = (15.39 \pm 0.021) \times 10^{-4}$ mu is well known from a series of measurements done by Mattauch. From these two mass-spectroscopic doublets, one obtains the difference

$$(N^{14}H—N^{15}) - (H_2—D) = N^{14} + D - H - N^{15} = (9.237 \pm 0.021) \text{ mmu}.$$

This, in the mass scale, is exactly the same quantity as that measured in the energy scale by the nuclear reaction. Therefore: (8.55 ± 0.08) Mev $= (9.237 \pm 0.021)$ mmu or 1 mmu = (0.926 ± 0.009) Mev. Thus we have obtained a value differing from the one predicted by the equivalence principle only by half a per cent with a probable error of about 1%.

This comparison is not the only one possible today, of course. However, it is amazing that there are not as many examples as one might expect from the large and increasing number of nuclear reactions. There are several reasons for this situation.

First, for only a rather small part of the reactions known are the reaction energies well established by reliable and accurate measurements. It is not sufficient to have a rough knowledge of them with a probable error of, say, 10%, if one wants to confirm the conversion factor with a somewhat higher accuracy. Thus, most reactions with fast neutrons are unsuited for such comparison.

Mass-spectroscopic Data

On the other hand, mass-spectroscopic material is much less suitable. Doublets consisting of mass lines of one doubly charged and one singly charged ion with half its mass, *e.g.*, A^{40++}—Ne^{20+}, are entirely useless for such a comparison, since there are no nuclear reactions connecting two nuclei with so widely differing masses. Furthermore, most of the older mass-spectroscopic precision values are disfigured by systematic errors, thus considerably reducing the accuracy of the experimental material once more.

Many reaction energies and doublet spacings, which lend valuable support for the calculation of nuclear masses and mass defects, are completely useless, therefore, for our investigation.

The material available today consists of seven well-established cases like the one treated above in some detail, all based on mass-spectroscopic values of the Mattauch school, and three such cases from mass-spectroscopic studies of Bainbridge and Jordan, the energy values occurring from different sources.

There seems to be some slight systematic difference between these two groups of mass-spectroscopic values. The average of the seven Mattauch values leads to a conversion factor

$$1 \text{ mmu} = (0.931 \pm 0.004) \text{ Mev}$$

in complete agreement with the theoretical prediction from Einstein's equivalence principle stated above and with a probable error of less than half a per cent. The three Bainbridge-Jordan values give a somewhat smaller average of about 0.91 with a somewhat larger error. This seems to be by far the best quantitative check of the principle from transmutation data.

It is striking that the heaviest nucleus occurring in this material is Ne^{21}, a very light nucleus. Mass-spectroscopic precision data are still lacking for heavy or even for medium-sized nuclei. Some more information in the region between masses 20 and 40, where many reaction energies are well known, would be a help.

Fission

There is, of course, a group of nuclear reactions which involve neighboring elements, namely, the *fission* of uranium and other elements at the end of the Periodic Table. Unfortunately, the different reactions occurring when uranium nuclei divide under, say, neutron bombardment, cannot be separated from one another so as to obtain very accurate values for the different reaction energies. Besides, there is no exact knowledge of the pairs of complementary fragments primarily originating in fission, of the part of the reaction energy carried off by fission neutrons in each single case, or of the rest of the energy remaining in the form of excitation inside the fragments and appearing later as gamma radiation. Yet at least we can make a fair estimate of all these contributions; their sum surely is much less than the kinetic energy of the two fragments (*3*), the latter ranging to a maximum of about 180 Mev. Thus, the whole energy liberation during a uranium fission may be estimated to 180 or 200 Mev without much error.

On the other hand, one obtains from the mass-spectroscopic investigations of Dempster and Graves a difference between the mass defects of a very heavy nucleus like uranium and two nuclei of medium size, which are bound a little faster, amounting pretty nearly to 200 mmu. Therefore, the fission experiences lead to an equivalence of about 1 mmu = 1 Mev, and check the conversion factor within the somewhat large error limit of about 10%.

β-decay

It is obvious that *radioactive β-decay* can also be used to prove the equivalence principle. Unfortunately, this

method does not work in a similar manner to that involving the nuclear reactions mentioned previously, since it has not yet been possible to obtain radioactive nuclei in sufficient quantities for the mass spectrograph. Some conclusions—not very reliable, it is true—may, however, be drawn even now.

Let us take the β-decay of C^{14} as an example. The upper limit of electron energies has been redetermined lately (*4*) to $E^- = (0.154 \pm 0.004)$ Mev with fair accuracy. The reaction energy $Q = (0.55 \pm 0.03)$ Mev of the exoenergetic reaction $N^{14}(n,p)C^{14}$ is well known (*5*). Letting the element symbols stand for the masses or rest energies of the neutral atoms, we then have the two equations

$$C^{14} - N^{14} = n - H - Q$$

and $$C^{14} - N^{14} = E^-.$$

Eliminating the masses of C^{14} and N^{14} from these equations, we obtain the mass difference of neutron and hydrogen atom in the energy scale:

$$n - H = E^- + Q.$$

Further, one gathers from the photodisintegration of the deuteron (*6*), *i.e.*, from $D(\gamma,n)H - E_D$ with $E_D = (2.237 \pm 0.005)$ Mev in the same scale, the sum

$$n + H = D + E_D.$$

Eliminating the neutron mass from these two relations, one finds in the energy scale the difference

$$H_2 - D = E_D - E^- - Q.$$

On the other hand, this difference is a well-known mass-spectroscopic doublet, *viz.*

$$H_2 - D = (1.539 \pm 0.0021) \text{ mmu}.$$

A comparison of the two values permits a new check of the conversion factor.

Unfortunately, for only one β^--emitting isotope are both E^- and Q known accurately enough; that is, the example of C^{14}. With the numerical values mentioned, this isotope leads to $H_2 - D = (1.53 \pm 0.04)$ Mev, which seems to be somewhat too large. The value E_D used here is a new value, but a smaller value of 2.19 or even 2.17 Mev that a year ago seemed more probable would lead to a much better fit in the conversion factor. Thus, such a comparison may be useful not only for the check it provides on our principle, but also for the information it may yield on nuclear physics constants.

Positron-emitters

Of course, not only β^--decay but also positron-emitters can be used for such determinations in a quite analogous way. The only difference is that, with positron-emitters, the mass of the electron occurs in the mass balance, but as this mass is known very exactly to be $m = 0.548$ mmu, there is no objection to the use of these decay processes. The results, however, are not very reliable, and in all of the about 10 cases where such a comparison is at all possible, the accuracy is even worse than with β^--decay.

Pair Production

These nuclear transmutations are not the only means of checking our principle. The most striking check seems to be the production of matter from energy and the opposite process. Unfortunately, up to now, we know with certainty only one such process: pair-production by γ-radiation, which includes the inverse process of annihilation radiation produced by the vanishing of the positron. The quantitative accuracy of energy measurements in both cases is not very good.

Pair production was investigated in detail by Chadwick, Blackett, and Occhialini (*7*), who measured the energies of the secondary electrons and positrons of the γ-rays of ThC'' ($h\nu = 2.62$ Mev) emitted by a layer of lead from the curvature of the tracks in a cloud chamber. As this method leads primarily to the momentum of each particle, the relativistic connection between momentum and energy is supposed.

Rather than investigate single particles, they made up statistics of all electrons as well as of all positrons, 4,000 tracks in all. They found an experimental upper limit of the electrons at $E^- = (2.49 \pm 0.04)$ Mev, and of the positrons at $E^+ = (1.55 \pm 0.03)$ Mev.

The energy limit of the electrons seems to be due to photoelectrons from the layer and, as the binding energy of the K-shell of lead is $E_K = 0.09$ Mev, the theoretical expectation is

$$E^- = h\nu - E_K$$
$$= 2.62 - 0.09 = 2.53 \text{ Mev},$$

which is slightly higher than the limit observed. As this small difference might arise from a small systematic error in the evaluation of the tracks, and as the same error will probably then occur in the positron limit

$$E^+ = h\nu - 2mc^2,$$

one will get the most reliable results from the difference

$$E^- - E^+ = 2mc^2 - E_K,$$

a quantity which will probably be independent of such errors, and which, besides, will no longer depend on the γ-energy $h\nu$. Since $m = 0.548$ mmu is well known in the mass scale, and $E^- - E^+ + E_K = (1.03 \pm 0.05)$ Mev is determined in the energy scale by this experiment, one obtains a conversion factor of

$$1 \text{ mmu} = (0.94 \pm 0.05) \text{ Mev}$$

in close agreement with the theoretical value.

The error in this determination, however, is about 5%. One might use other γ-rays instead. But then, for relatively small γ-energies, the probability of pair production will be small and large statistical errors may occur. For large γ-energies, on the other hand, the difference $(E^- - E^+)$ will be small compared to the values of E^- and E^+ themselves and a large error will result in this difference.

The latter difficulty occurs in a paper by Fowler, Gaerttner, and Lauritsen (*8*), who used the γ-rays liberated by proton-bombardment of boron to determine the energies of the γ-quanta from their Compton recoil electrons as (4.3 ± 0.3), (11.8 ± 0.5), and (16.6 ± 0.6) Mev. They investigated 68 pairs produced by these γ-rays. Pair energies of (3.1 ± 0.1), (10.5 ± 0.1), and (15.3 ± 0.1) Mev may be deduced from a drawing in their paper. The difference of the γ-ray energies and the respective pair energies should equal $2mc^2$, or $2m$ in the mass scale. Thus, the three differences of (1.2 ± 0.3), (1.3 ± 0.5), and (1.3 ± 0.6) Mev have to be compared to $2m = 1.096$ mmu, which again shows that the conversion factor lies near 1 Mev = 1 mmu, but that the accuracy becomes worse the higher the γ-energy used.

Solution of this problem becomes possible today with the availability of X-ray equipment with energies above 1 Mev. Pairs can be created, in spite of the small probability, with sufficient intensity to allow even precision measurements.

The inverse process, the absorption of a positron by an electron, and the *annihilation* of both of them, may also be useful for our purpose. The situation is somewhat simpler because the positron is generally absorbed only after being slowed down by ionization processes. As a matter of fact, it was only in 1946 that the annihilation of fast positrons was observed by Bothe and Ho (*9*). The annihilation of slow positrons always produces a radiation energy of $2mc^2$, and it can be shown easily, considering the conservation of momentum, that this amount always will be equally distributed on two light quanta, each of energy mc^2.

One, therefore, needs no more than a determination of the quantum energy of such annihilation radiation to obtain a new check of our equivalence principle by comparison with the electron mass. Early experiments by Joliot (*10*) led to

(*Continued on bottom of next page*)

CROSS SECTIONS

Design of Electron Guns for Synchrotrons *

With betatrons and synchrotrons, the present limitation on electron current and X-ray output at high energy is set by the difficulty of injecting a sufficient number of electrons into stable orbits when the magnetic guide field is relatively weak. The important requirements of an electron gun are proper optics, a cathode designed to have high peak emission, the ability to hold a high-voltage pulse, and a reasonable life in service.

Initially, on the 80-Mev synchrotron now in use in Schenectady, a betatron gun with a wolfram filament and a simple geometry was employed. Because of the low electron emission from pure wolfram, such filaments are operated at a rather high temperature to obtain peak X-ray output. Evaporation and embrittlement of the wolfram may limit the cathode life to something like 125 hours. Because of the high pulsed emission which is possible with oxide-coated cathodes, it was thought that oxide cathodes would be ideal for the accelerator guns. However, it was found that they had several other unsatisfactory characteristics. The oxide coating was pulled off by the high electric fields and was sputtered away by positive ion bombardment, both of which greatly reduced the active life of the cathode. The activity of an oxide cathode is also subject to deterioration on repeated exposure to air.

A modification of a dispenser cathode was tried with more encouraging results. In order to obtain a higher resistance than is possible with the

* From a report (AECU 547) by J. M. Lafferty and H. C. Pollock, General Electric Research Laboratory.

(*Continued from preceding page*)

a quantum energy of (485 ± 60) kev with an efficiency of between 1.6 and 3 γ-rays per positron annihilated, which fits the theoretical value of 2 γ-rays and $m = 0.548$ mmu, and thus may be looked upon as another rough check of our principle.

Gathering up all details, it remains somewhat amazing that all these transmutation data do not give more reliable results on so basic a principle. However, no strong contradiction to the theoretical value is so far known.

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stocking mesh, the cathode was made from a closely-wound helix of molybdenum wire, as shown in Fig. 1. The helix could be made square in cross section or with a curved re-entrant portion, depending on the optical requirements of the gun.

Barium aluminate was used as the active material for filling the helix. This may be done in several ways. The usual procedure is to use small pieces of the crushed material. This works well when the stocking, or helix, is 0.175 in., or larger in diameter. For smaller sizes it is difficult to pack the particles sufficiently close together to obtain any appreciable density. In this case it was found desirable to press up a block of barium aluminate with 3% wax. The block is baked at 1,375° C for one hour in a hydrogen furnace, and may then be inserted in the molybdenum helix. The large amount of barium aluminate thus stored in the center of the cathode insures a long life. Any barium which is sputtered away by positive ion bombardment is replaced from the large reservoir in the helix. Since there is only a monolayer of barium on the emitting surface of the molybdenum cathode, there is no danger of active material being pulled off by the strong electric fields.

When the cathode is first heated, a considerable amount of gas is evolved. The cathode may be brought up to operating temperature, which is approximately 1,350° C, within 15 or 20 minutes. Subsequently, the filament may be heated very quickly, unless it has been exposed to air, in which case the slow heating is again advisable.

The electron gun was designed for insertion through a radial arm. It has a barium aluminate cathode and electron optics to give a focused beam. Tests made on guns of this type in all the accelerators in Schenectady have proved very satisfactory. The X-ray output with the 80-Mev synchrotron

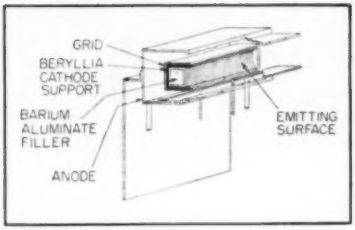

FIG. 1.

has been as high as 500 r per minute, as measured with a Victoreen thimble placed in ⅛ inch of lead at a distance of 1 meter from the target. With the 100-Mev betatron 4,000 r per minute has been obtained.

Observation of the current pulse from the gun cathode shows that the instantaneous currents are of the order of 500 milliamperes. Usually it is convenient to measure the average emission, a portion of which goes to the anode and a portion to the conducting coating of the tube. Data taken with the synchrotron to determine how X-ray output depends on emission current and gun voltage show an increase of output with gun voltage.

In general the gun is placed so as to put the cathode near the radial position where $n = 1$ in the expression for the field $H \propto r^{-n}$, with r the radial distance of the gun anode from the magnet center. The output decreases when the gun is moved away from this position. It is possible to obtain X-ray output when a gun is inserted radially through an inner arm so that its cathode is in the field region where n is approximately ¼. However, with the gun positioned in this way the current which can be successfully injected has been lower by at least one order of magnitude.

Injection can also be accomplished with the cathode and anode both placed above the median plane of the accelerator tube. This arrangement may be desired when it is planned to expand

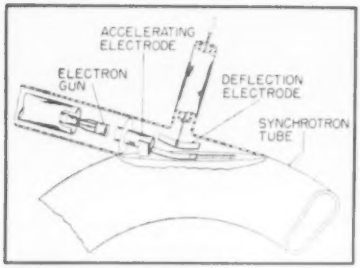

FIG. 2.

the electron orbit late in the acceleration cycle to bring the electrons into a beam extractor located in the median plane. A gun developed for this purpose has the cathode current brought through the glass stem using a piece of ¼-inch O.D. molybdenum tubing and a concentric 50-mil molybdenum wire to form the leads. The gun end of the tubing is arced to the cathode shield box. One end of the filament helix is welded to the 50-mil lead and the other end of the helix to the cathode shield box. The vacuum seal around the wire is made with a glass bead where the wire enters the molybdenum tubing about 2½ inches from the cathode. Small beads steady the wire in the tubing.

This concentric construction reduces the dimensions of the cathode support while increasing both the mechanical and electrical strength. It eliminates much of the 60-cycle vibration resulting from interaction of filament current with guide field. Guns of this type have given outputs approximately ⅓ that obtained with the previously described type.

Some time ago J. P. Blewett proposed that injection from standard guns might be improved by pulsing positively a third electrode mounted near the opening of the anode through which the injected beam passes. By pulsing this electrode positively the beam can be deflected outward slightly, thus permitting electrons to enter almost tangentially orbits which will just clear the back of the gun. Guns of this type have been successfully used for some months, particularly with the 50-Mev biased betatron in this laboratory.

The "three electrode" gun has recently been carried further in the design of Fig. 2. In this gun design the cathode structure is removed several inches from the orbit. The initial gun of this type has been successfully used with the 80-Mev machine.

Uranium Detected by Airborne Prospectors

Present techniques of airborne prospecting for uranium are reported* to include, in large part, methods developed by the Geological Survey for determining the position of an observation, and of recording the data obtained by aeromagnetic surveying.

In addition, refinements commonly used in measuring cosmic radiation have been adopted. For example, background noise due to cosmic radiation had to be cut down. This is accomplished by a thick one-inch lead shield above the Geiger counters to reduce the soft component of cosmic radiation, while a special arrangement of counter tubes in hexagonal bundles directly below the lead shield, allows the hard component to be reduced.

It is said to be impossible at the moment to state the sensitivity of this particular equipment. But with a radium source and by extrapolation, the standard deviation at normal levels of measurement is 0.3 micro-roentgens per hour.

Since radioactive radon gas is known to escape from radioactive ores, an

(Continued on page 90)

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* In talk by Frank W. Stead, Geological Survey, before meeting of A.I.E.E., New York, Feb. 1.

BOOKS

Spectroscopic Properties of Uranium Compounds (Div. III, Vol. 2, of National Nuclear Energy Series), by G. H. Dieke and A. B. F. Duncan, McGraw-Hill Book Co., Inc., New York, 1949, xvii + 290 pages, $2.75. *Reviewed by B. F. Scribner, Chief, Spectrochemistry Section, National Bureau of Standards.*

This book is largely an account of advances in the knowledge of absorption and fluorescence spectra of uranium compounds resulting from one phase of the extensive Manhattan Project. The literature on uranyl compounds is surveyed thoroughly up to 1943, and new material obtained at Columbia and Johns Hopkins Universities in 1943 and 1944 is presented.

The spectroscopic section of the book occupies 200 pages, of which 80 pages are appended tables of wavelengths. One fifth of the book is devoted to chemical preparation and growth of crystals for most of the 55 compounds studied.

The work is characterized by considerably improved wavelength measurements made on sharp-line spectra obtained at liquid hydrogen temperature and with high spectral dispersion. Many strong lines were classified, but more extensive classification awaits new data.

Both the chemist and physicist will be interested in the preparations and studies made of isotopically substituted uranium compounds. Substitutions of isotopes of U, O, N and H were of considerable assistance in identifying types of vibrations and in determining molecular structure.

The Characteristics of Electrical Discharges in Magnetic Fields, (Div. I, Vol. 5, of National Nuclear Energy Series), edited by A. Guthrie and R. K. Wakerling, McGraw-Hill Book Company, Inc., New York, 1949, xviii + 376 pages, $3.50. *Reviewed by J. D. Cobine, Research Laboratory, General Electric Company, Schenectady, N. Y.**

This book is essentially a collection of technical reports of the atomic energy program that, under normal publishing conditions, would probably have appeared as a series of scientific papers. Much of the book is concerned with a low-pressure "arc" in new and rather specialized surroundings. This discharge consists of a beam of electrons accelerated from a filament and collimated by a slot as it enters a graphite box and is subjected to a longitudinal magnetic field. The plasma formed by the beam is studied under various conditions of pressure, magnetic field, beam current, *etc.* The conclusions of some derivations are only partially verified by experiment.

An introductory chapter serves to orient the reader and to provide a loose organization of the balance of the material presented. Chapter 2 presents both the characteristics of probes used to explore plasma and the theoretical considerations of the phenomena involved, with special attention being given to the effect of a magnetic field. A new theory is developed that gives order-of-magnitude agreement with experiment for electron and positive ion currents to a probe on a magnetic field. Chapters 3 and 4 present brief theoretical considerations of the sheath region about electrodes, and of the minimum pressure for a stable arc in a magnetic field. The characteristics of arcs near the threshold pressure for a stable arc with magnetic field are presented in Chapter 5 for A, He, and SF_6. Two

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* NUCLEONICS wishes to acknowledge the courtesy of the editors of the *General Electric Review* in permitting simultaneous publication of this commentary.

mechanical diagrams are difficult to understand because of unconventional presentation.

The apparatus and experimental results of a study of the cross sections for ionization of UCl_4 and UF_6 by electron collisions up to 500 ev are discussed in Chapter 6. The results for UF_6 are inconclusive. A study of the ionization and dissociation products and their appearance potentials of UCl_4 and UF_6 under electron impact is presented in Chapter 7.

Chapter 8 presents a brief consideration of the rate of ion production by an electron beam. Chapter 9 presents a diffusion theory of the arc plasma in a magnetic field together with a large amount of new experimental data on the phenomena associated with this type of discharge. Special attention is given to the effect of potential distribution on ion losses from the plasma. Considerable space is devoted to the presentation of the characteristics of the oscillations and electrical noise (called by the technical slang term "hash") present in the discharge. The statement is made that "A great amount of work has resulted in no real understanding of the nature of hash. . . . " (p. 345). However, no reference is made to OSRD reports and papers on this subject published since the war.

The use of discharges as sources of electrons is considered in Chapter 10. The theory and operation of the Philips ionization-gage type of discharge is given in Chapter 11. The index is adequate but references throughout the book are sketchy.

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Analysis and Design of Experiments, by H. B. Mann, Dover Publications, Inc., New York, 1949, 195 + x pages, $2.95.

Dissociation Energies and Spectra of Diatomic Molecules, by A. G. Gaydon, Dover Publications, Inc., New York, 1950, 239 + vii pages, $3.95.

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OTHER LITERATURE

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Commutator Motor, by F. J. Teago, $1.25; *Hyperfine Structure in Line Spectra and Nuclear Spin*, by S. Tolansky, $1.50; *X-ray Optics*, by A. J. C. Wilson, $1.50; *Mercury Arcs*, by F. J. Teago and J. F. Gill, $1.50; *Fundamentals of Discharge Tube Circuits*, by V. J. Francis, $1.50; *An Introduction to the LaPlace Transformation*, by J. C. Jaeger, $1.50; *Cosmological Theory*, by G. C. McVittie, $1.50; *Magnetism*, by E. C. Stoner, $1.25; *The Cyclotron*, by W. B. Mann, $1.25; *Physical Constants*, by W. H. J. Childs, $1.25; *The General Principles of Quantum Theory*, by G. Temple, $1.25; *Low Temperature Physics*, by L. C. Jackson, $1.50.

Civil Defense Against Atomic Attack: Preliminary Data (February, 1950). Preliminary report released by Joint Committee on Atomic Energy, 81st Congress, 2d Session, for use of the committee in its hearings on civil defense. (*U. S. Congress, Joint Committee on Atomic Energy, Washington, D. C.*)

Safe Handling of Radioactive Isotopes (National Bureau of Standards Handbook H42). Prepared by the National Committee on Radiation Protection, established by the National Committee on Radiation Protection, this handbook gives general safety recommendations that may be modified to suit the control requirements of different types of operations in the typical laboratory or small industrial operation using radioisotopes. Specific problems discussed are those of personnel, laboratory design and equipment, hazard instrumentation, hazard monitoring, and transportation of isotopes. *Available from Superintendent of Documents, U. S. Govt. Printing Office, Washington 25, D. C., 15 cents.*

Bibliography of Occupational Medicine, Vol. 1, 1948. With this volume, the first to be issued since the outbreak of World War II in 1939, the International Labor Office, Geneva, is resuming publication of its international index of references to major books and articles dealing with all aspects of industrial health and welfare. It is intended to issue future numbers of the bibliography on a quarterly basis. *Available from Washington Branch, International Labor Office, 1825 Jefferson Place, N.W., Washington 6, D. C.*, $1.

Atomic Energy Commission Document Sales Agency Price List No. 15. A listing of all publications made available for sale during the last quarter of 1949. *Copy of price list available without cost from U. S. Atomic Energy Commission Document Sales Agency, Box 62, Oak Ridge, Tenn.*

NEW SCIENCE SERVICE OFFERED PROFESSIONALS AND LAYMEN

Of interest to professionals and students in every field of science is this new time-saving service recently offered by the Science Book and Information Service, 471 Orange Street, S.E., Washington 20, D. C.:

(*1*) A worker specializing in any field may use its personal book-information section designed to meet his individual requirements.

(*2*) Those who have been seeking rare or out-of-print books may secure them through the service.

(*3*) Anyone who wants to be kept continuously up to date on developments, whether in a specific subject or in general science, may readily do so through the regular bulletins, issued monthly. These bulletins, available separately in each subject, supply comprehensive information (summaries, descriptions, listings), on every scientific and technical book of importance in the field, whether already published or forthcoming.

The SBIS also services its members by supplying desired books upon request. END

NUCLEONIC EVENTS

MOST POWERFUL CYCLOTRON STARTS OPERATION

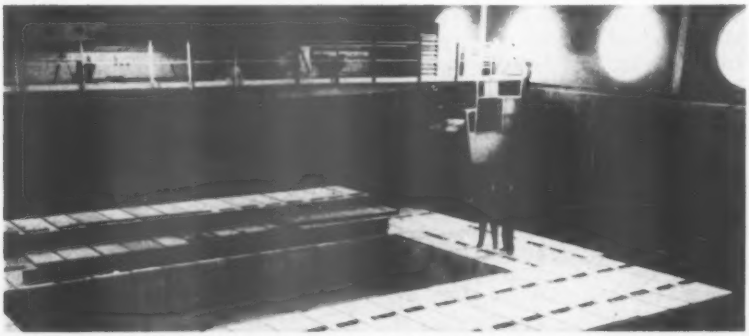
On February 28, the world's most powerful synchrocyclotron, generating 385 Mev, started operation at Columbia University's new nuclear physics research center at Irvington-on-Hudson, New York. To be used primarily as a research tool, the machine has already functioned perfectly in producing mesons. The cyclotron's major components are its 2,500-ton magnet, vacuum system, radio-frequency system, structures concerned with the proton beam, control system, and 1,000 cu yd (2,000 tons) of concrete shielding. The magnet, whose pole pieces are 170 in. in diameter, has an 18-in. gap and is of 0.085% carbon steel with major dimensions of $14 \times 33 \times 21$ ft.

Excitation for the magnet is provided by current flowing through 12 pancake coils of copper strap. A 600-kw motor-generator set provides 1,870 amp for a total of 1.12×10^6 amp-turns, resulting in a field of 17,500 gauss. The coils are cooled by a flow of 2,000 gal of special oil, which, in turn, is cooled by a maximum flow of 1,000 gal per min of water taken from the Hudson River in heat exchangers in the machine bay.

The cyclotron accelerates protons which are formed from hydrogen gas in an arc source in the middle of the chamber.

The cyclotron itself cost $2,500,000, of which the Office of Naval Research contributed $1,400,000 and the Atomic Energy Commission $700,000. Columbia University provided the land, laboratory buildings, and most of the accessory equipment.

The building housing the cyclotron and the laboratory in which accessory equipment is located are situated on the grounds of Nevis, a 68-acre estate on the banks of the Hudson River. To be known as the Nevis Cyclotron Laboratory, it will function under John R. Dunning as scientific director and E. T. Booth as executive director.



General view of shielding which surrounds Columbia University's 385-Mev cyclotron. At rear shielding is about 30 ft thick

HOUSE PASSES NATIONAL SCIENCE FOUNDATION BILL

A bill to establish a National Science Foundation was finally passed by the House of Representatives last month, six years after President Roosevelt initiated studies of the problem. A similar measure was passed by the Senate March 18, 1949. The differences in the bills will be worked on in conference.

The House made two important changes in the bill as presented by Chairman Crosser of the Commerce Committee. Appropriations for the Foundation were limited to $500-thousand for the first year (as allowed in the budget) and outlays thereafter to $15-million annually. No definite amount was named in the Senate bill.

A tight loyalty check was included in the bill in an amendment offered by Howard W. Smith (D., Va.) requiring individual FBI clearance of every employee of the Foundation and the same careful screening of holders of scholarships awarded by the agency. Considerable opposition to this amendment is being encountered. It is reported possible that the amendment could cause defeat of the bill.

The Foundation would be barred from supporting any atomic energy research or development activity.

ELEMENT 98, CALIFORNIUM, IDENTIFIED AT U. OF CALIFORNIA

Discovery of element 98, another synthetic unit of matter which does not exist in nature and has never before been observed on earth, was reported last month by University of California scientists working under contract with the Atomic Energy Commission.

Named *californium* after the university and the state, it is the heaviest atom ever known, standing six steps up the periodic table from uranium, the most massive atom in nature. It was made by bombarding curium, element 96 (at weight 242) with 35-Mev alpha particles, fired from the university's 60-inch Crocker cyclotron.

Not enough of element 98 was made in the bombardment to be visible; indeed, the weight of the curium target was only a few millionths of a gram. It decays by emitting alpha particles, and has a 45-min half-life.

The researchers who reported the discovery are Dr. Stanley G. Thompson,

ABOUT THE COVER

THE University of Illinois' new 300-Mev betatron, shown in the background of the cover photo, will be among the major equipment needed for what scientists are calling the "open season on mesons." The betatron's inventor, Donald W. Kerst, appears in the foreground with his 2½-Mev original machine.

The new betatron, recently put in operation, weighs 400 tons and has a vacuum-tube diameter of 9 ft and power consumption of 150 kw. The original betatron, by comparison, weighs 200 lb, has an 8-in tube, and uses 5 kw. Artificial cosmic rays can be produced in Dr. Kerst's new machine 14-billion times more concentrated than those showered on the earth by nature. The world's largest betatron, it has an operating level 20 times that of similar electron accelerators. Photo from University of Illinois.

Kenneth Street, Jr., Albert Ghiorso, research chemist, and Dr. Glenn T. Seaborg, professor of chemistry, all of the Radiation Laboratory and Department of Chemistry.

This is the same group, with the exception of Mr. Street, which announced only last January the discovery of element 97, named berkelium. Bombardments which produced the new element were made by a group in the Crocker Laboratory, in charge of Dr. Joseph G. Hamilton, associate professor of medical physics.

Dr. Seaborg explained the near-simultaneous discovery of elements 98 and 97 can be attributed to the similarity of the problems of marking them. He pointed out that the discoveries of the other synthetic elements have followed a similar pattern.

ALLIES PASS LAW TO PERMIT GERMAN ACCELERATORS, PILES

The Western Allied High Commission recently issued a law on control of the use of atomic energy. Work in this field by German research, educational and medical establishments will be permitted under strict security regulations.

The law forbids the production, importation, exportation, transportation, storage, use and possession of radioactive materials, except for investigative purposes, within existing regulations.

The law permits the manufacture or construction of electronuclear machines capable of imparting energies up to 100 Mev to a positively charged particle or to an ion. It also permits the construction or erection of nuclear reactors or facilities capable of separating isotopes of uranium with a yield potential up to one milligram of U^{235} every 24 hours.

OAK RIDGE TO HOLD SUMMER CHEMISTRY COURSE

The second annual summer symposium, sponsored jointly by the Oak Ridge National Laboratory and the Oak Ridge Institute of Nuclear Studies, will be held at Oak Ridge from August 21 to September 1. Devoted to inorganic and physical chemistry, the symposium will emphasize modern concepts of electronic structure, binding, valence, and related subjects.

Although the program will serve principally as a refresher course for college chemistry teachers, it will be open to others. Details of the program are being worked out by G. E. Boyd, M. A. Bredig, K. A. Kraus, and H. A. Levy, all of the chemistry division of ORNL.

FLUOR CORP. TO BUILD MATERIALS TESTING REACTOR

The Atomic Energy Commission recently announced that contract negotiations are being conducted with the Fluor Corporation, Limited, of Los Angeles, California, for construction work on the materials testing reactor to be built at the Reactor Testing Station near Arco, Idaho.

The contract being discussed with Fluor covers more than 50 percent of the construction cost estimated to be at least $20,000,000. The balance of the work will be let on competitive bidding. The Fluor portion of the contract includes the reactor itself, the reactor building and auxiliary facilities directly connected with operation of the reactor.

AEC SPONSORS NEW FELLOWSHIP PROGRAM

A new predoctoral fellowship program requiring research subjects to be closely allied to the atomic energy field will be sponsored by the Atomic Energy Commission in the biological and physical sciences during the 1950–51 academic year. The program will be administered on a regional basis by institutions located in the northeast, southeast, midwest and west.

The new program will differ from that administered by the National Research Council for the AEC during

the 1949–50 academic year in that the subjects of research must be sufficiently closely related to atomic energy to justify a presumption that the candidate, upon completion of his studies, will be especially suited for employment by the AEC or one of its contractors. However, neither the AEC, its contractors nor the fellows are under any obligation to offer or accept such employment.

FEDERAL GOVT. TO HOLD AIR POLLUTION CONFERENCE

Because of the technical problems arising from atmospheric contamination, President Truman has directed Secretary of the Interior Oscar L. Chapman to convene the first U. S. Technical Conference on Air Pollution. Sponsored by the Federal Interdepartmental Committee on Air Pollution, the conference will be held in Washington, D. C., on May 3, 4 and 5.

Panel sessions on the following subjects will be held: meteorology, health, instrumentation, equipment, analytical methods and properties, legislation and agriculture.

NUCLEAR PHYSICS SYMPOSIUM TO BE HELD AT OAK RIDGE

A symposium on "Nuclear Physics of the Light Elements" will be held at Oak Ridge National Laboratory, on June 8 and 9. The subject matter will be keyed to the researches currently in progress with the aid of electrostatic generators and other high voltage machines.

The invited speakers and their topics are as follows:

H. H. Barschall, University of Wisconsin, *Study of Nuclear Energy Levels by Fast Neutrons;* T. W. Bonner, Rice Institute, *Information on Energy Levels as Derived from Neutron Thresholds, Excitation Curves, Gamma Rays and Disintegration Particles;* W. W. Buechner, Massachusetts Institute of Technology, *Results on Ground States and Excited States from Magnetic Analysis Experiments;* R. F. Christy, California Institute of Technology, *Theoretical Aspects;* W. A. Fowler, California Institute of Technology, *Current Work at Kellogg Radiation Laboratory;* and A. Hemmendinger, Los Alamos, *Interaction of Tritons with Protons and Tritons.*

S. K. Allison, University of Chicago, and R. G. Herb, University of Wisconsin, will act as chairmen. Inquiries should be addressed to the Director, Physics Division, Oak Ridge National Laboratory, P. O. Box P, Oak Ridge, Tennessee.

INTERNAT'L CHEMICAL MEETINGS SCHEDULED FOR N. Y. IN 1951

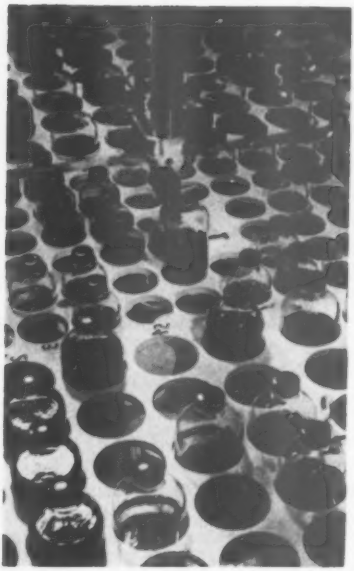
Chemists and chemical engineers from more than thirty countries will assemble in New York in September, 1951, to participate in the largest international chemical conclave in history, it is announced by Ernest H. Volwiler, president of the American Chemical Society, which will celebrate its diamond jubilee at that time.

Both the Sixteenth Conference of the International Union of Pure and Applied Chemistry and the Twelfth International Congress of Pure and Applied Chemistry will convene following the seventy-fifth anniversary meeting of the American Chemical Society, scheduled for the week of September 2.

This combination of international meetings will be the first of its kind in the United States since 1912, although the International Union met in Washington in 1926 when the American Chemical Society marked its golden jubilee. Part of the Union's 1951 meeting will be conducted in Washington.

James Bryant Conant, president of Harvard University and a former professor of chemistry there, has been named honorary president of the Twelfth International Congress, at which world

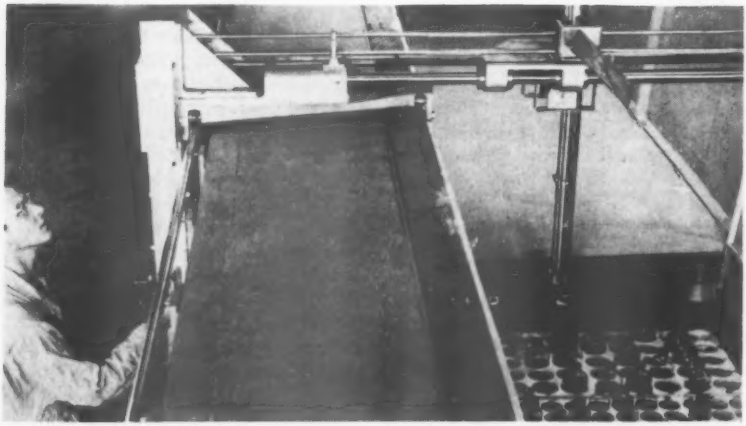
(Continued on p. 84)



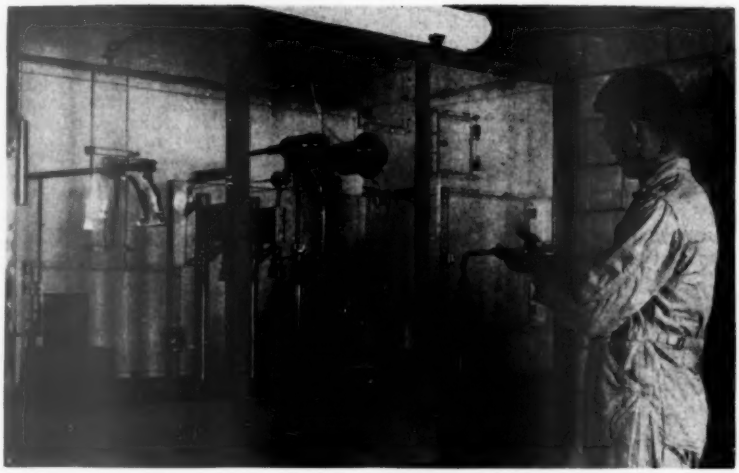
1 **Bottles** of radioisotope solutions stored in indexed trays are kept behind concrete barriers, visible in picture below

5 **Filled** bottle is removed from turntable with packing tongs. After activity is measured, it will be packed for shipping

How Oak Ridge



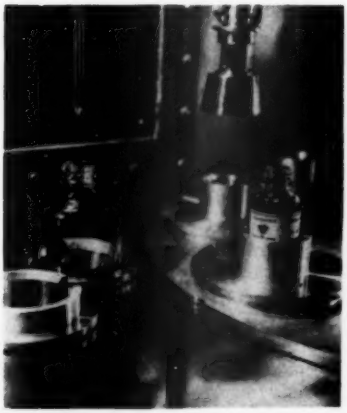
2 **Sectional lids** above trays, opened and closed by remote control, prevent flow of contaminated air. Protected by concrete barrier two-feet thick which shields storage trays, operator controls tongs. Periscope and mirrors enable him to see over wall to locate desired bottle, pick it up and move it to remotely controlled pipetting device



4 **Low-activity** isotopes do not require such bulky shielding, are transferred to shipping containers inside hood shielded with transparent plastic. Operator uses extension holder to place storage bottle of phosphorus-32 inside opened hood

Handles Isotopes

To protect personnel from over-long exposure to radiation while handling isotopes, Oak Ridge National Laboratory has devised a remote-control system. These pictures by J. E. Westcott of AEC's photography unit at Oak Ridge show the devices and methods used to prepare both high and low activity radio-isotope solutions for shipment



3 **With storage** and shipping bottles placed on turntables, operator outside barrier controls decapping device, top right, and pipette to transfer the isotope

progress in every field of chemical science and technology will be reported. The Congress is held every four years to enable leaders in the various branches of chemistry and chemical engineering to exchange information.

The International Union, which meets every two years to set uniform chemical standards for scientists and engineers throughout the world, will decide questions of nomenclature, atomic weights, and the like. Hugo R. Kruyt of The Hague, The Netherlands, is president of the Union.

OAK RIDGE TO HAVE SOUTHEAST'S FIRST CYCLOTRON

The first cyclotron in the Southeast, an 86-inch machine for the acceleration of protons to 20 Mev, will be ready for use around May 1 at Oak Ridge National Laboratory, according to an announcement by the Atomic Energy Commission.

The cyclotron will be located in the electromagnetic plant area so that advantage can be taken of an existing building and some of the equipment originally installed for the separation of U^{235} by the electromagnetic process. The electromagnetic process is now in stand-by, although research on process improvement is being carried forward.

PRINCETON SYNCHROCYCLOTRON BADLY DAMAGED BY FIRE

The 18-Mev synchrocyclotron at Princeton University was seriously damaged by fire on February 22. The fire was reported to have started in the 400 gallons of transformer oil which is used to cool the machine.

Built in 1935, the machine had been partially dismantled during the war. Under the direction of Dr. Milton G. White, professor of physics, it took three years to rebuild it. Dr. White estimates that it will take two years to go through this same rebuilding process.

TWO ATOMIC ENERGY PAPERS SCHEDULED FOR POWER MEETING

Two papers on atomic energy—by Sir John Cockcroft, director of Great Britain's Atomic Energy Research Establishment at Harwell, and by M. Kowarsky, of France's Commissariat à l'Energie Atomique—are among the more than 150 reports to be discussed at the Fourth World Power Conference to be held in London from July 10 to 15, 1950. Thus far, no American paper on this subject has been planned.

This will be the first full-scale meeting of the World Power Conference since its meeting in Washington in 1936. The first three meetings were held at intervals of six years, but this timetable was interrupted by the recent war.

T. E. MURRAY NAMED AEC COMMISSIONER

Thomas E. Murray, business executive and engineer, was recently nominated by President Truman to fill David E. Lilienthal's unexpired term as a member of the Atomic Energy Commission. He will serve as commissioner under Sumner T. Pike who is acting chairman.

NUCLEAR NEWSMAKERS

William H. Ray, formerly of the Health Physics Division of Oak Ridge National Laboratory, has been named research associate in the Dept. of Occupational Health of the University of Pittsburgh,

H. Kirk Stephenson, a geophysicist who has worked at Argonne National Laboratory, and **Charles H. Perry,** formerly in the Health Physics Group at Oak Ridge, have been appointed to the staff of Los Alamos Scientific Laboratory.

Dwight E. Gray, former supervisor of technical reports and liaison of the Applied Physics Laboratory of Johns Hopkins University, Silver Spring, Md., has joined the staff of the Technical

Information Branch of the AEC in Washington, D. C., as technical advisor to TIB chief Alberto Thompson.

Robert Hofstadter, assistant professor of physics at Princeton University, will become associate professor of physics at Stanford University on September 1.

Robert E. Marshak, professor of physics at the University of Rochester, has been appointed chairman of the Department of Physics to replace **George B. Collins,** who has resigned to head large-scale accelerator work at Brookhaven National Laboratory. Announced at the same time were the appointments of **Sidney W. Barnes** as administrator of the 250-Mev cyclotron project and **S. N. Van Voorhis** as professor of physics in charge of the 7-Mev cyclotron project.

Robert S. Neblett, assistant general manager of the General Electric Co.'s Nucleonics Department, has been appointed business and construction manager of the Knolls Atomic Power Laboratory, and **Robert O. Bullard** has been named as his assistant. **R. G. Lorraine** has been named a project head.

F. W. Schuler, with the Manhattan Project, during the war, has joined the National Research Corp., Cambridge, Mass., to do metallurgical research.

Hamnett P. Munger of Battelle Memorial Institute has been appointed to coordinate the institute air-pollution research activities and to act in a liaison capacity between Battelle and industry.

John Z. Bowers, special assistant to the director of the Division of Biology and Medicine of the AEC, stationed at Berkeley, has been appointed dean of the University of Utah College of Medicine, effective November 1. **Charles L. Dunham** has been promoted to the position of chief of the Medical Branch to fill the position Dr. Bowers held prior to shifting to Berkeley. **John A. Derry** has been appointed to the newly established position of executive officer of the division.

H. W. Koch has been appointed to the Radiation Physics Section of the National Bureau of Standards, where he will be in charge of the research program utilizing the new 50-Mev betatron and the 180-Mev synchrotron, which will soon be available.

IN BRIEF

➤The application of atomic energy to large-scale industrial uses will necessitate the construction of many new communities and the replanning of old ones, according to Dr. Amos H. Hawley, professor of sociology at the University of Michigan. Using funds from the university's Memorial-Phoenix Atomic Energy Project, he will study the problem of what happens to the plans for a new community after they leave the hands of the designer.

➤*"The output of fundamental research is deploringly small as compared to the size and power of our industrial laboratories," I. M. Kolthoff of the University of Minnesota stated recently. A lag in fundamental research produces a lag in industrial application.*

➤Establishment of a Mexican atomic energy commission has been recommended by Jose T. Baez, a scientist and member of the National Association of Mexican Technicians. The recommended project would center around a large particle accelerator.

➤*It is reported that within one year the Indian government will have in operation a factory for processing raw materials for the atomic energy field.*

➤A recent AEC census has revealed that the city of Richland, Washington, where the Hanford Engineer Works is located, has a population estimated at 22,089. END

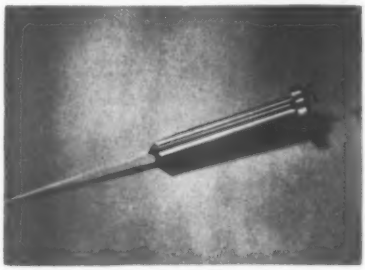
PRODUCTS and MATERIALS

CABLE CONNECTORS

Atomic Instrument Co., 160 Charles St., Boston, Mass. Designed for use with preamplifiers operating at moderately high voltages, six models of a multi-circuit connector have insert bodies molded from melamine. The six contact pins of each connector are precision machined and silver plated. The center contact is a "make first, break last" type, and is said to provide additional safety when connected to a grounding wire. Standard "AN" shells and fittings are keyed to provide positive polarization. A six-conductor cable has also been developed for use with these connectors. Jacketed with neoprene, the ½-in. diameter cable has six color-coded conductors, three of which are shielded and rated at 2,500 rms volts. Two 1,000-volt conductors and a coaxial cable with Teflon dielectric complete the cable.

MAGNETIC AMPLIFIER

Vickers Electric Division, 1815 Locust St., St. Louis, 3, Mo. A demonstration magnetic amplifier, catalog number 36A34, is arranged so that all basic single-phase self-saturating circuits may be studied. By arrangement of the external connections either d-c or a-c output is available, and either d-c or a-c control power may be used. Besides its educational use, the unit may be used in operating control circuits, such as voltage regulators, motor speed controls, and servomechanism positioning systems. Reference material and bulletins are included with each unit.



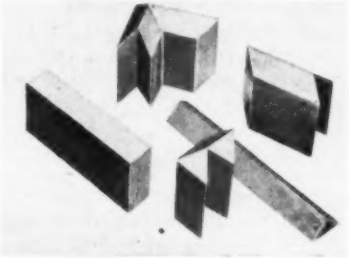
PROBING COUNTER TUBE

Ballantine Laboratories, Inc., Boonton, N. J. Originally designed for use in neurological surgery, these probing G-M tubes are also applicable to other medical and biophysical uses requiring a probe of minimum size. The stainless steel probing needle has an outside diameter of 2 mm. Its wall thickness is approximately 65 mg/cm². Sensitive volume of the counter tube is near the end of the needle, starting about 5 mm from the tip and extending to about 18 mm from the tip. The total needle length of 10 cm is graduated in 1-cm divisions starting at the distant end of the sensitive volume, as an aid in determining depth of penetration. The ½-in. diameter brass handle also serves as a gas reser-

voir. Its brass cap carries a metal-glass insulator for the anode connection, and a copper exhaust tube which also serves as the cathode connection. With a starting voltage of 1,050 volts ±10%, the tube has a plateau length of 75–100 volts and a plateau slope of 10% per 100 volts. Pulse size at 50 volts above threshold is one volt minimum with 30 $\mu\mu$f input capacitance.

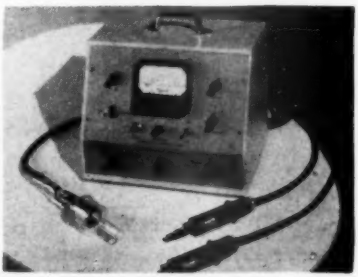
PROPORTIONAL CONVERTER

Nuclear Measurements Corp., 3339 Central Ave., Indianapolis 5, Ind. The model PCC-10 proportional counter converter can be used to convert any standard scaler which embodies a suitable high-voltage supply, to a proportional counter. It consists of a counting chamber, amplifier, pulse-height selector, high-voltage connector, leakproof bubbler, and low-voltage plug and cable. The counting chamber is designed to permit counting of evaporated salts, precipitates, compressed pellets, and ashed samples with 2π geometry. Maximum sample size is 1⅜ in. in diameter and 3/16 in. thick. Decontamination is said to take only ten minutes. The alpha plateau extends from 1,000 to 1,300 volts, and the beta plateau extends from 1,600 to 1,900 volts. Both have a slope of less than 2% per 100 volts average; in the best 100 volts, slope is less than 0.5%. Power requirements for the converter are 300 volts d-c at 20 ma, regulated 150 volts d-c at 6 ma, 6.3 volts a-c at 1.4 amp, and a regulated high-voltage supply variable from 800 to 2,000 volts. Cabinet dimensions are 6⅜ in. wide by 8 in. high by 12 in. deep.



INTERLOCKING BRICKS

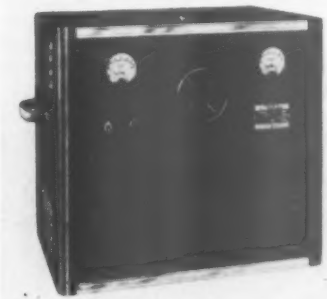
Nuclear Instrument and Chemical Corp., 223 W. Erie St., Chicago 10, Ill. Designed for background shielding, model 3039 interlocking lead bricks are said to eliminate the low-density "joint space" common to rectangular bricks. Four different shapes are available for building up completely dense walls. Provision is made for corners and similar construction. A triangular filler is available to fill up the low-density area at the bottom of the structure.



ION GAGE CONTROL

National Research Corp., 70 Memorial Drive, Cambridge, Mass. The type 710 thermocouple and ion-gage control utilizes two thermocouple-type and an

ionization-type vacuum gage to measure pressures ranging from 1 mm to 1×10^{-8} mm Hg absolute. Each of the thermocouple gages indicates pressures from 1 mm to 1×10^{-3} mm Hg directly on the control meter. The ionization gage covers the range from 5×10^{-3} to 1×10^{-8} mm Hg in five steps. Full-scale readings at 5×10^{-3}, 1×10^{-4}, 1×10^{-5}, and 1×10^{-6} mm give normal sensitivity, while, for pressures below 5×10^{-7}, normal sensitivity can be doubled. A low-leakage shielded connecting cable is said to eliminate errors at low pressures. A protective relay with very short time delay automatically turns off the gage filament when the pressure in the system exceeds 1½ times full-scale pressure. Provision is made for using this relay to control operation of alarm bells or pump heater circuits. Filament emission can be adjusted to 1, 5, or 10 ma. An outgassing circuit is also provided.

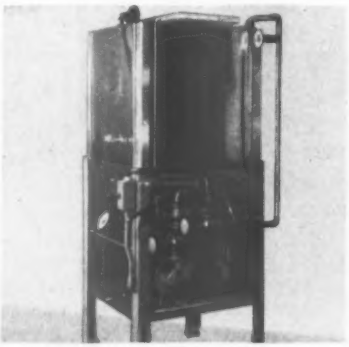


D-C VOLTAGE SUPPLY

Superior Electric Co., Hannon Ave., Bristol, Conn. Operating from a 95–135 volt, 60-cycle a-c line, the Varicell provides a d-c output that is variable from 0 to 30 volts. Allowable output current at any voltage setting is 15 amperes. Output voltage is stabilized and regulated to within 0.25% at settings between 6 and 30 volts. Ripple voltage is said to be less than ±0.1 volts.

ANTHRACENE CRYSTALS

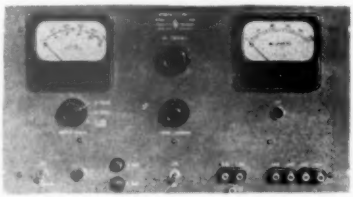
Reilly Tar & Chemical Corp., 11 S. Meridian St., Indianapolis, Ind. Developed in cooperation with Dr. George B. Collins of the University of Rochester physics department, Reilly scintillation grade anthracene is said to be of unusually high purity. It is free of those impurities which usually prevent the growing of large, clear crystals used in scintillation counting equipment.



GLASSWARE WASHER

Heinicke Instrument Corp., 315 Alexander St., Rochester 4, N. Y. Designed to impart a turbulent scrubbing motion to wash and rinse solutions, the model HW-1000 laboratory glassware washer is designed to clean an estimated 5,000 or more test tubes, or 1,500 Petri dishes per hour. Washing capacity for larger glassware is somewhat lower. Glassware is held in Monel-metal baskets which are rotated over wash jets. A second set of jets above the baskets counteracts the lower ones, holding the glassware in place and, at the same time, cleaning surfaces not exposed to the lower jets. An entirely

separate system of jets is used for rinsing, and provision is made for prewash rinsing. A detergent dispenser automatically maintains the wash-water concentration at the proper level. Perforated brass trays are used to catch solid debris, so that neither drains nor pump will become clogged. The washer is loaded at table height, and doors on three sides make a flow-through system possible.



HIGH-VOLTAGE SUPPLY

Hewlett-Packard Co., 395 Page Mill Rd., Palo Alto, Calif. The model 712A power supply provides variable direct voltages from 0 to 500 volts at 200 ma with 0.5% regulation, and 0 to 150 volts for bias use. A 10-ampere a-c supply at 6.3 volts is also provided. Meters are provided to monitor voltages and currents. The unit is available in a cabinet or for relay rack mounting.

DIFFUSION PUMP

Distillation Products Industries, Rochester 3, N. Y. The MCF-60 high-vacuum pump provides an evacuating speed of 60 liters per second in the range 10^{-5} to 10^{-3} mm of mercury, and an ultimate vacuum of 5×10^{-7} mm. The vapor jets are said to operate against a forepressure of 0.2 mm or more, depending on the heater input. An external heating unit is provided for the water-cooled casing. With no fixed compartments in the over-sized boiler, the three-stage, concentric-cylinder type fractionating jet assembly can, it is claimed, be easily removed for cleaning.

LITERATURE AVAILABLE

Synthetic Waxes. Tables giving solubility, specific gravity, melting point, color, flash point, acid value, and use data are included in this 16-page catalog of synthetic waxes. *Glyco Products Co., 26 Court St., Brooklyn 2, N. Y.*

Containers for Liquefied Gases. Folder describes available sizes and construction of all-metal containers and unbreakable metal Dewar vacuum flasks for liquefied gases. *Superior Air Products Co., 132 Malvern St., Newark 5, N. J.*

Acid-proof Construction. Bulletin describes construction of tanks, chemical equipment, floors, sewers for acid processes, and lists acid-proof cements, bricks, and coatings. *Electro-Chemical Supply and Engineering Co., Paoli, Pa.*

Power Supplies. Folder lists data on electronically-regulated power supplies with power output from 1.5 to 500 watts and voltage output as high as 1,500 volts. Data for a klystron power supply is also listed. *Furst Electronics, 12 S. Jefferson St., Chicago 6, Ill.*

Laboratory Instruments. Z-angle meters, phase meters, r-f oscillators, and precision potentiometers are described in this booklet. Also included is an outline of design procedure for nonlinear potentiometers. *Technology Instrument Corporation, 1058 Main St., Waltham 54, Mass.*

Counter-rotating Mixer. Brochure describes a two-propeller mixer designed for laboratory use. *Brookfield Engineering Laboratories, Porter St., Stoughton, Mass.*

Bibliography E-90(1). Over 2,000 references to polarographic analysis in the literature are listed chronologically and cross-indexed by author and subject. *Leeds & Northrup Co., 4934 Stenton Ave., Philadelphia 44, Pa.*

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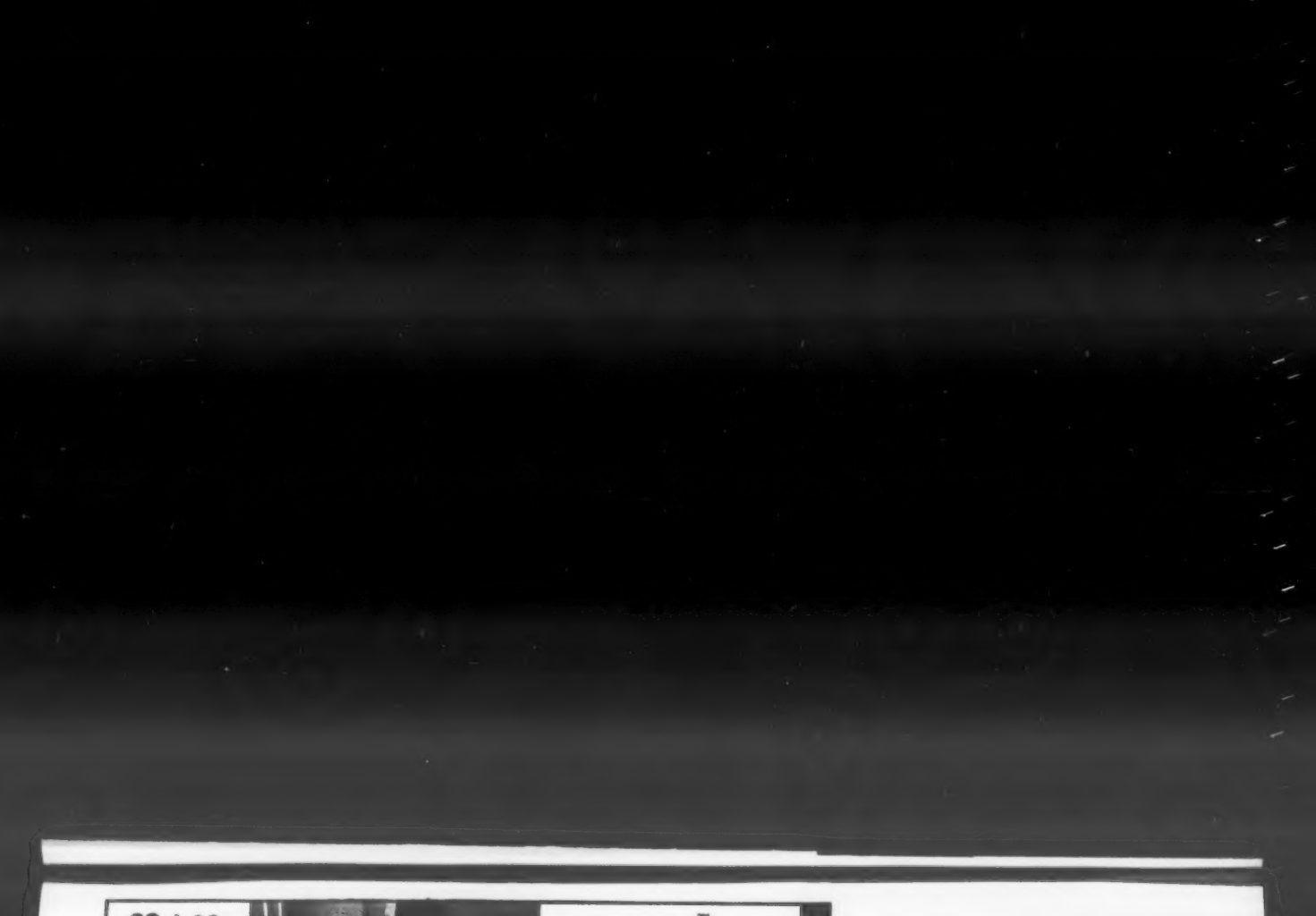
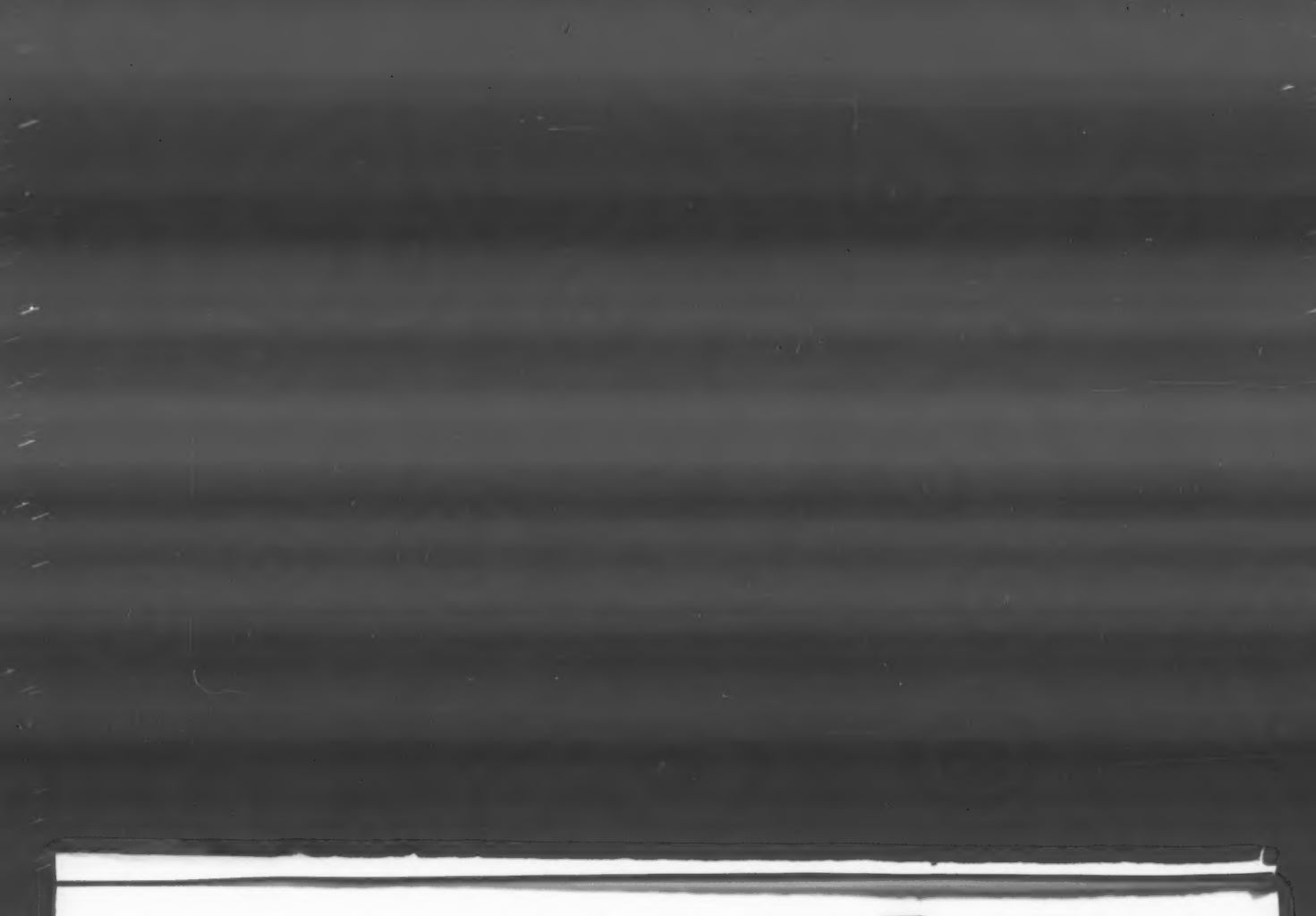
Cross Sections *(Cont. from p. 74)*

arrangement is also made to monitor the atmosphere through which the prospecting plane flies. Air flow from an intake in the nose of the plane is led back to an air conductivity meter. This is a cylindrical condenser with the inner coaxial member connected to a vibrating reed electrometer. An amplifier and Brown recorder for the meter are mounted on a table behind the intake duct. In this way it is hoped the ionization of the atmosphere by radon escaping from ores can be measured.

As might be expected, such elaborate and complicated equipment installed in a plane involves considerable weight. Roughly this is about 1,400 pounds, exclusive of the power source. Obviously, this equipment and that used in subsurface explorations are beyond the reach of the average prospector and are intended for use by large organizations.





NUCLEAR ENERGY GLOSSARY

Biophysics and Radiobiology

THE TERMS defined on the following pages have been selected from Section VI (Biophysics and Radiobiology)* of *A Glossary of Terms in Nuclear Science and Technology*.† Those terms that are units of measurement are grouped under the heading "Units" on pages 107–108.

The glossary was prepared through the efforts of participants in the National Research Council Nuclear Glossary Conference, the story of which was published in the March, 1950, NUCLEONICS.‡

Users of these terms are invited to send suggestions and criticisms to the Chairman of the NRC Glossary Conference, National Research Council, 2101 Constitution Avenue, Washington 25, D. C., for consideration in making a further review and revision for a later publication of all sections, possibly in a single book.

The section from which the following terms have been selected has been issued as a "Preliminary Edition" and designated by the American Standards Association as a "Proposed American Standard."

NUCLEONICS acknowledges the assistance of Dr. Edith H. Quimby in making its selection of terms from Section VI.

Activated water. The passage of ionizing radiation through water produces, temporarily, ions, atoms, radicals, or molecules in a chemically reactive state. The combined effect of all such entities is said to be due to activated water. Their identity has not been established with certainty, although evidence exists for the presence of free hydroxyl radicals and hydrogen atoms.

Acute exposure. Denotes radiation exposure of short duration.

Agranulocytosis. Complete or nearly complete absence of granulocytes from blood and bone marrow.

Air dose **(X-rays).** X-ray dose expressed in roentgens delivered at a point in free air. In radiologic practice, it consists only of the radiation of the primary beam, and that scattered from surrounding air.

Air-wall ionization chamber **(X- or gamma rays).** Ionization chamber in which the materials of the wall and electrodes are so selected as to produce ionization essentially equivalent to that in a free-air ionization chamber. This is possible only over limited ranges of photon energies. Such a chamber is more appropriately termed an air-equivalent ionization chamber.

* Members of the Section VI Review Committee, appointed to act for the NRC Glossary Conference, were: Edith H. Quimby (Chairman), Columbia University; Howard L. Andrews, National Institutes of Health; Sterling B. Hendricks, U. S. Department of Agriculture; Alexander Hollaender, Oak Ridge National Laboratory; and Lauriston S. Taylor, National Bureau of Standards.

† Copyright 1950 by the National Research Council and published by the American Society of Mechanical Engineers, 29 West 39th Street, New York 18, N. Y. Selections from the Glossary are published here with the permission of these two organizations.

‡ Published previously in NUCLEONICS were terms selected from Section V, "Chemical Engineering" (NU, Mar. '50, pp. 91–96).

Annihilation radiation. Photons produced when an electron and a positron unite and cease to exist. The annihilation of a positron-electron pair results in the production of two photons, each of at least 0.5-Mev energy.

Associated corpuscular emission. (Expression used in definition of roentgen, *q.v.*). The full complement of secondary charged particles (usually limited to electrons) associated with an X-ray or gamma-ray beam in its passage through air. The full complement of electrons is obtained after the radiation has traversed sufficient air to bring about equilibrium between the primary photons and secondary electrons. Electronic equilibrium with the secondary photons is intentionally excluded.

Autoradiograph (**Radioautograph**). Record of radiation from radioactive material in an object, made by placing its surface in close proximity to a photographic emulsion.

Autoradiography. The production of autoradiographs.

Average life (**Mean life**). The average of the individual lives of all the atoms of a particular radioactive substance. It is 1.443 times the radioactive half-life.

Backscatter. Scattering of radiation in a generally backward direction. In radiation therapy it is particularly applied to radiation scattered back to the skin from underlying tissues. In the assay of radioactivity, it applies to the scattering of particles into the measuring device by the material on which the sample is mounted.

Biologic half-life (**of a radioactive substance**). The time in which a living tissue, organ, or individual eliminates, through biologic processes, one-half of a given amount of a substance which has been introduced into it. (See *Effective half-life*).

Bone seeker. Any compound or ion which migrates *in vivo* preferentially into bone.

Carcinogenesis. Production of cancer.

Carcinoma. Malignant neoplasm composed of epithelial cells, regardless of their derivation.

Carrier (**isotopes**). An isotope or the normal isotopic mixture of an element, when mixed with radioactive atoms of the same element, in such a form that it undergoes the same chemical reaction. Carriers are often added deliberately for radiochemical purposes.

Carrier-free. A preparation of a radioactive isotope which for practical purposes is essentially free from stable isotopes of the element in question.

Cataphoresis. (See *Electrophoresis.*)

Chronic exposure. Denotes radiation exposure of long duration, by fractionation or protraction. (See *Dose fractionation* and *Dose protraction*)

Columnar ionization. Regions of such dense ionization that even a strong external electric field cannot prevent some recombination. The term refers usually to ionization produced by alpha particles.

Condenser r-meter (**condenser ionization chamber**). Ionization instruments for measuring X- or gamma rays, consisting of an electrometer and a detachable ionization chamber, embodying a condenser of suitable capacitance. This can be attached to the electrometer and the entire system charged. It is then detached from the electrometer, exposed to the radiation and thereby partly discharged, and returned to the electrometer for reading the decrease in charge. The instrument can be calibrated to read directly in roentgens at the position of the center of the chamber, over a considerable range of photon energies, provided the ionization chamber is suitably constructed.

Contamination (**radioactive**). Deposition of radioactive material in any place where it is not desired, and particularly in any place where its presence may be harmful. The harm may be in vitiating the validity of an experiment

or a procedure, or in actually being a source of danger to personnel.

Cumulative dose **(radiation).** The total dose resulting from repeated exposures to radiation of the same region, or of the whole body.

Decay constant. (See *Disintegration constant*)

Depth dose. The radiation dose delivered at a particular depth beneath the surface of the body. It is usually expressed as percentage of surface dose or as percentage of air dose (*q.v.*).

Differential absorption ratio. Ratio of concentration of an isotope in a given organ or tissue to the concentration that would be obtained if the same administered quantity of this isotope were uniformly distributed throughout the body.

Disintegration constant. The fraction of the number of atoms of a radioactive isotope which decay in unit time. λ in the equation $N = N_0 e^{-\lambda t}$, where N_0 is the initial number of atoms present.

Dose **(dosage).** According to current usage, the radiation delivered to a specified area or volume, or to the whole body. Units for dose specification are roentgens for X- or gamma rays, and reps or equivalent roentgens for beta rays. The subject of dose units for particulate radiation and for very-high-energy X-rays has not been settled. In radiology, the dose may be specified in air, on the skin, or at some depth beneath the surface; no statement of dose is complete without specification of location. The entire question of radiation dosage units is under consideration by the International Congress of Radiology, and it is expected that new units based on the energy absorbed in tissue will be adopted. (See individual definitions for *Air dose, Cumulative dose, Depth dose, Integral dose, Permissible dose, Skin dose, Threshold dose, Tissue dose, Tolerance dose.*)

Dose fractionation. A method of administration of radiation in which relatively small doses are given daily or at longer intervals.

Dose meter **(dosimeter).** Any instrument which measures radiation dose.

Dose protraction. A method of administration of radiation by delivering it continuously over a relatively long period at a low dosage rate.

Dose rate **(dosage rate).** Radiation dose delivered per unit time.

Effective atomic number. A number calculated from the composition and atomic numbers of a compound or mixture. An element of this atomic number would interact with photons in the same way as the compound or mixture. Various formulas for this number have been developed, of which the following are perhaps best known:

Spier: Based on theoretical considerations involving absorption and scattering coefficients [*Brit. J. Radiol.* **19,** 52 (1946)]. Z = effective atomic number $= (a_1 Z_1^{2.94} + a_2 Z_2^{2.94} + \cdots)^{1/2.94}$, where Z_1, Z_2, etc., are atomic numbers of individual constituents, and a_1, a_2, *etc.*, are the fractional electron contents of elements Z_1, Z_2, *etc.*, in the compound.

Fricke and Glasser: Based on theoretical considerations of photoelectron production [*Fortsch. a.d. Gebiete der Roentgenstrahlen* **33,** 243 (1925)]

$$Z = \sqrt[3]{\frac{a_1 Z_1^4 + a_2 Z_2^4 + \cdots}{a_1 Z_1 + a_2 Z_2 + \cdots}}$$

where Z_1, Z_2, *etc.*, are the atomic numbers of the constituents, and a_1, a_2 are their fractions by weight.

Effective half-life. Half-life of a radioactive isotope in a biological organism, resulting from the combination of radioactive decay and biological elimination: *Effective half life* = (Biological half-life × Radioactive half-life) ÷ (Biological half-life + Radioactive half-life).

Electrophoresis. *Cataphoresis:* The migration of charged particles through a fluid under the influence of an electric field. *Iontophoresis:* The introduction of ions into the tissues of the body by the use of electric currents.

Epilation (**depilation**). The temporary or permanent removal of hair.

Equivalent constant potential (**X-rays**). The constant potential which must be applied to an X-ray tube to produce radiation having an absorption curve in a given material closely similar to that of the beam under consideration.

Erythema. An abnormal redness of the skin, due to distension of the capillaries with blood. It can be caused by many different agents, *e.g.*, heat, certain drugs, ultraviolet rays, ionizing radiations.

Erythrocyte. A red blood corpuscle.

Exit dose. Dose of radiation at surface of body opposite to that on which the beam is incident.

Extrapolation ionization chamber. An ionization chamber designed to make a series of measurements, in which one factor is varied in suitable steps. The data derived from these measurements are plotted in appropriate form and the desired result is obtained by extrapolation of the curve. The construction of such a chamber depends on the problem to be investigated.

In general, the chamber consists of two electrodes (plane, cylindrical, or spherical) uniformly separated from each other. One of the electrodes has an ion-collecting surface of known area and a guard plate or ring to insure proper electric field distribution. The ion-collecting volume is defined by the collecting area and the separation of the electrodes.

In the measurement of tissue dose, where it is necessary to determine the ionization in an infinitesimal air cavity, the separation of the electrodes is changed in steps from a minimum practical value to a value that will provide a good curve for extrapolation to zero electrode separation (that is, zero collecting volume).

In an extrapolation chamber designed for the measurement of the dose at the surface of the skin in X-ray therapy, the electrodes are parallel planes and the one on the incident side of the beam can be varied in thickness. A double extrapolation can then be performed: (*1*) with respect to electrode separation, and (*2*) with respect to electrode thickness.

Field emission. Emission of electrons from unheated metal surfaces produced by sufficiently strong electric fields.

Film badge. A pack of photographic film used for approximate measurement of radiation exposure, for personnel-monitoring purposes. The badge may contain two or three films of different sensitivity, and it may contain a filter which shields part of the film from certain types of radiation.

Film ring. A film badge in the form of a finger ring.

Filter (**radiology**). *Primary:* A sheet of material, usually metal, placed in a beam of radiation to absorb, as far as possible, the less penetrating components. *Secondary:* A sheet of material of low atomic number relative to that of the primary filter, placed in the filtered beam of radiation to remove characteristic radiation produced in the primary filter. (See also *Thoraeus filter*)

Filtration (**radiology**). Removal of some components of a heterogeneous beam of radiation by passage through a sheet of material. The filtering effect of any substance depends on its absorption coefficients for photons of various energies. Any filter will remove definite proportions of radiation of all wavelengths, but always a greater fraction of the longer wavelengths, except near critical absorption regions of the material and in the region where pair production becomes predominant.

Fluorescent screen. A sheet of material coated with a fluorescent sub-

stance emitting visible light when irradiated with ionizing radiation.

Free-air ionization chamber. An ionization chamber in which a delimited beam of radiation passes between the electrodes without striking them or other internal parts of the equipment. The electric field is maintained perpendicular to the electrodes in the collecting region; as a result the ionized volume can be accurately determined from the dimensions of the collecting electrode and the limiting diaphragm. This is the basic standard instrument for X-ray dosimetry at least within the range from 5-400 kv.

Genetic effect of radiation. Inheritable changes, chiefly mutations, produced by the absorption of ionizing radiations. On the basis of present knowledge these effects are purely additive, and there is no recovery.

Half-life **(radioactive).** (See *Radioactive half-life*)

Half value layer. The thickness of any particular material necessary to reduce the dose rate of an X-ray beam to one-half its original value.

Hardness **(X-rays).** A term for qualitatively specifying the penetrating power of X-rays. In general, the shorter the wavelength the harder the radiation.

Health physics. A term in common use for that branch of radiological physics dealing with the protection of personnel from harmful effects of ionizing radiation. It includes the routine procedures of radiation protection surveys, area and personnel monitoring, the recommendation of appropriate protective equipment and procedures, the determination of acceptable standards of operation, and the solution of problems incident to the effective and practical protection of all persons from harmful effects of radiation. Out of this last phase has grown the study of environmental hazards, including the accumulation of radioactive material by plants and animals, and possible injury to human beings ultimately utilizing these in food chains.

Hit theory. (See *Target theory*)

Implant. *In radiology:* Radioactive material in a suitable container, to be embedded in a tissue for therapeutic purposes. It may be permanent (seed) or temporary (needle). *In biology:* Tissue or organ removed to an abnormal position; a graft.

Inherent filtration **(X-rays).** The filtration introduced by the wall of the X-ray tube and any permanent tube enclosure; to be distinguished from added primary and secondary filters.

Integral dose **(volume dose).** A measure of the total energy absorbed by a patient or any object during exposure to radiation. According to British usage, the integral dose for X- or gamma rays is expressed in gram-roentgens (*q.v.*)

Integrating dose meter. Ionization chamber and measuring system designed for determining total radiation administered during an exposure. In medical radiology the chamber is usually designed to be placed on the patient's skin. A device may be included to terminate the exposure when it has reached a desired value.

Intensifying screen. Sheet of cardboard or other material coated with fluorescent material, placed in contact with the film in radiography. The X- or gamma rays excite the fluorescent substance and the light thus emitted adds to the radiation effect on the film and produces an image of greater density for a given exposure. Sheets of thin lead may be used for the same purpose in industrial radiography with very-high-energy radiation. In this

case, the increased effect is due largely to secondary electrons and X-rays emitted by the lead.

Intensity **(radiology).** Amount of energy per unit time passing through unit area perpendicular to the line of propagation at the point in question. Often this term is used incorrectly in the sense of dose rate (*q.v.*)

Inverse voltage **(X-ray tube).** The voltage impressed across the X-ray tube during the half cycle when the anode is negatively charged.

Ion. Any electrically charged particle of molecular, atomic or nuclear size.

Ionization. The process whereby a neutral atom or molecule is split into positive and negative ions.

Ionization chamber. An instrument designed to measure quantity of ionizing radiation in terms of the charge of electricity associated with ions produced within a defined volume. This is usually done by measuring the quantity of electricity in the form of ions carried to the chamber electrodes when a suitable potential difference is established between them. [See individual definitions for *Air-wall ionization chamber*, *condenser r-meter* (*ionization chamber*), *Extrapolation ionization chamber*, *Free-air ionization chamber*, *Monitor ionization chamber*, *Tissue-equivalent ionization chamber*, and *Thimble ionization chamber*.]

Ionization density. Number of ion pairs per unit volume.

Ionization path **(or *track*).** The trail of ion pairs produced by an ionizing particle in its passage through matter.

Ionizing radiation. Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, in its passage through matter.

Iontophoresis. (See *Electrophoresis*).

Irradiation. Exposure to radiation. One speaks of *radiation therapy*, but of *irradiation* of the patient.

Isodose chart. Chart showing the distribution of radiation in a medium by means of lines or surfaces drawn through points receiving equal doses. Isodose charts have been determined for beams of X-rays traversing the body, for radium applicators used for intracavitary or interstitial therapy, and for working areas where X-rays or radioactive isotopes are employed.

Keloid. Excessive scar formation following irradiation or other forms of skin injury.

Latent period **(radiology).** Interval between irradiation and appearance of the effect in question.

Latent tissue injury **(radiology).** Injury which does not become manifest until some time after irradiation, and possibly not until some other trauma has supervened. This second injury may be so slight that it would not, of itself, produce observable damage.

LD 50 dose. (See *Median lethal dose*).

LD 50 time. (See *Median lethal time.*)

Lead equivalent. The thickness of lead affording the same reduction in radiation dose rate under specified conditions as the material in question.

Leukemia. A disease in which there is often great overproduction of white blood cells, or a relative overproduction of immature white cells, and great enlargement of the spleen. The disease is variable, at times running a more chronic course in adults than in children. It is almost always fatal, although its progress can sometimes be delayed by radiation or by chemical agents. It can be produced in some animals by long-continued exposure to low intensities of ionizing radiation.

Median lethal dose. **(*MLD* or *LD 50 dose*).** Dose of radiation required to kill, within a specified period, 50%

of the individuals in a large group of animals or organisms.

Median lethal time **(*MLT or LD 50 time*).** Time required following administration of a specified dose of radiation for death of 50% of the individuals in a large group of animals or organisms.

Metastasis. Growth in the body of malignant neoplastic cells at a distance from the original or parent cancer.

Monitoring. Periodic or continuous determination of the amount of ionizing radiation or radioactive contamination present in an occupied region, or in a person, as a safety measure for purposes of health protection. (See also *Protection survey.*)

Area Monitoring: Routine monitoring of the level of radiation or of radioactive contamination of any particular area, building, room, or equipment. Usage in some laboratories or operations distinguishes between routine monitoring and survey activities.

Personnel Monitoring: Monitoring any part of an individual, his breath, or excretions, or any part of his clothing.

Monitor ionization chamber. (*1*) An ionization chamber mounted in an X-ray beam and connected to a continuously reading instrument, to serve as an indicator of X-ray output. (*2*) An ionization chamber used to detect the presence of undesirable radiation in connection with health protection.

Monochromatic radiation. Electromagnetic radiation of a single wavelength, or in which all the photons have the same energy.

Monoenergetic radiation. Particulate radiation of a given type (alpha, beta, neutron, *etc.*) in which all particles have the same energy.

Neoplasm. A new growth of cells which is more or less unrestrained and not governed by the usual limitations of normal growth. *Malignant:* If the growth invades tissues of host, spreads to distant parts, or both. *Benign:* If there is some degree of growth restraint and no spread to distant parts.

Penetrometer **(radiology).** A device for measuring penetrating power of a beam of X-rays or other penetrating radiation by comparing transmission through various absorbers.

Percentage depth dose. Amount of radiation delivered at a specified depth in tissue, expressed as a percentage of the amount delivered at the skin.

Periosteum. The tough fibrous membrane surrounding bone; a place of frequent radiation injury.

Permissible dose. The amount of radiation which may be received by an individual within a specified period with expectation of no harmful result to himself. For long-continued X- or gamma-ray exposure of the whole body, it is 0.3 roentgen per week measured in air. (For detailed information, see National Bureau of Standards Handbooks 41 and 42, and a forthcoming publication.)

Phantom **(radiology).** A volume of material behaving in essentially the same manner as tissue, with respect to the radiation in question, used to simulate a portion of the human body, and into which ionization chambers can be placed. Measurements made in a phantom permit the determination of the radiation dose delivered to the skin and points within the body. Materials commonly used for X-rays are water, Masonite pressed wood (unit density), or beeswax.

Protection **(radiology).** Provisions designed to reduce exposure of personnel to radiation. For external radiation, this consists in the use of protective barriers of radiation-absorbing material, in ensuring adequate distance from radiation sources, in reducing exposure time, or in combinations of these. For internal sources, it involves

measures to restrict inhalation, ingestion, or other modes of entry of radioactive materials into the body.

Protection survey. Evaluation of the radiation hazards incidental to the production, use, or existence of radioactive materials or other sources of radiation under a specific set of conditions. Such evaluation customarily includes a physical survey of the disposition of materials and equipment, measurements or estimates of the levels of radiation that may be involved, and a sufficient knowledge of processes using or affecting these materials to predict hazards resulting from expected or possible changes in materials or equipment.

Purpurae. Large hemorrhagic spots in or under the skin or mucous tissues.

Quality. A term for the approximate characterization of radiation with regard to its penetrating power. It is usually expressed in terms of effective wavelengths or half value layer (*q.v.*).

Radiation sickness. *In radiation therapy:* A self-limited syndrome characterized by nausea, vomiting, diarrhea, and psychic depression, following exposure to appreciable doses of ionizing radiation, particularly to the abdominal region. Its mechanism is unknown and there is no satisfactory remedy. It usually comes on a few hours after a treatment and may subside within a day. It may be sufficiently severe to necessitate interrupting the treatment series, or to incapacitate the patient.

In atomic bomb disaster: A syndrome following intense acute exposure to ionizing radiations. A few hours after exposure nausea and vomiting appear, last a few hours and then subside for a variable interval. After this quiescent period, a recurrence of nausea and vomiting is accompanied by mucous or bloody diarrhea, purpurae, epilation, and agranulocytic infections. The illness may vary in severity, and may go on to death, or partial or apparently complete recovery may ensue. The more intense the early symptoms and the shorter the period of remission, the more serious the final outcome.

Radiation therapy. Treatment of disease with any type of radiation. *Radiotherapy:* Treatment of disease with any ionizing radiation.

Radioactive half-life. The time in which the amount of a particular radioactive isotope is reduced to half of its initial value.

Radioactive tracer. Small quantity of radioactive isotope, either with carrier or carrier-free, used to follow biological, chemical or other processes. Since the stable and radioactive isotopes of an element have essentially the same chemical properties, and the radioactive ones are readily detected, the movement and behavior of the stable atoms can be traced by following the radioactivity. In this case, the compound under observation is said to be "labeled" with the radioactive isotope.

Radioautograph. (See *Autoradiograph.*)

Radiobiologic action. The effect of radiation upon living matter.

Radiobiology. That branch of biology which deals with the effects of radiation on biological systems.

Radiocolloid. A clumping of radioactive atoms into colloidal aggregates.

Radiography. The making of shadow images on photographic emulsion by the action of ionizing radiation. The image is the result of the differential absorption of the radiation in its passage through the object being radiographed.

Radiology. The medical science of radioactive substances, X-rays, and other ionizing radiations, and the application of the principles of this science to diagnosis and treatment of disease.

Radioresistance. Relative resistance of cells, tissues, organs, or organisms to the injurious action of radiation. The term may also be applied to chemical compounds or to any substances. (See also *Radiosensitivity*).

Radiosensitivity. Relative susceptibility of cells, tissues, organs, organisms, or any substances to the injurious action of radiation. Radioresistance and radiosusceptibility are at present employed in a qualitative or comparative sense, rather than in a quantitative or absolute one.

Radiotherapy. (See *Radiation therapy.*)

Recovery **(radiology).** The return toward normal of a particular cell, tissue, or organism, after radiation injury. Recovery may apparently be complete, or it may be partial.

Recovery rate. The rate at which recovery takes place following radiation injury. It may proceed at different rates for different tissues. *Differential recovery rate:* Among tissues recovering at different rates, those having slower rates will ultimately suffer greater damage from a series of successive irradiations. This differential effect is taken advantage of in fractionated radiation therapy if the neoplastic tissues have a slower recovery rate than surrounding normal structures.

Relative biological effectiveness of radiation (RBE). The inverse ratio of tissue doses of two different types of radiation that produce a particular biologic effect under otherwise identical conditions. In general, the RBE may vary with the kind and degree of biological effect considered, the duration of the exposure, and other factors.

Roentgen rays. X-rays (*q.v.*).

Scattered radiation **(in radiology).** Radiation which, during its passage through a substance, has been deviated in direction. It may also have been modified by an increase in wavelength.

Secondary radiation. Radiation originating as the result of absorption of other radiation in matter. It may be either electromagnetic or particulate.

Seed, radium. (See *Implant*)

Selective localization **(isotopes).** In the use of radioisotopes, accumulation of a particular isotope to a significantly greater degree in certain cells or tissues. (See *Differential absorption ratio*)

Sensitive volume **(*Sensitive region*** **(in radiology).** Part of a cell particularly sensitive to radiation. (See *Target theory*)

Skin dose **(radiation therapy).** Dose at center of irradiation field on skin. It is the sum of the air dose (*q.v.*) and back scatter (*q.v.*) with the addition of the exit dose (*q.v.*) from other parts, if this is significant.

Specific activity, gram element. Total radioactivity of a given isotope per gram of element.

Specific activity, isotope. Total radioactivity of a given isotope per gram of the radioactive isotope.

Specific ionization. Number of ion pairs per unit length of path of the ionizing particle in a medium, *e.g.*, per centimeter of air or per micron of tissue.

Stray radiation. Radiation not serving any useful purpose. It includes direct radiation (*q.v.*) and secondary radiation from irradiated objects.

Supervoltage. In radiology, a term applied to radiation generated by X-ray tubes operating at voltages in the range from 500 to 2,000 kv.

Survival curve. (*1*) Curve obtained by plotting number or percentage of organisms surviving at a given time against dose of radiation. (*2*) Curve showing percentage of individuals surviving at different intervals after a particular dose of radiation.

Target theory **(hit theory.)** Theory explaining some biologic effects of radiation on basis of ionization occurring in a very small sensitive region within the cell. One, two, or more "hits," *i.e.*,

ionizing events within the sensitive volume (*q.v.*) may be necessary to bring about the effect.

Thimble ionization chamber. A small cylindrical or spherical ionization chamber, usually with walls of organic material.

Threshold dose. The minimum dose that will produce a detectable degree of any given effect.

Tissue dose. Dose received by a tissue in the region of interest. In the case of X-rays and gamma rays, tissue doses are expressed in roentgens. At the present time there is no generally accepted unit of tissue dose for other ionizing radiations. In radiobiological studies it is customary to think of the tissue dose in terms of the energy absorbed per gram of tissue. Several units related to the roentgen have been suggested, such as the rep (*q.v.*).

Tissue-equivalent ionization chamber. Ionization chamber in which the material of the walls, electrode, and gas are so selected as to produce ionization essentially equivalent to that characteristic of the tissue under consideration. In some cases it is sufficient to have only tissue-equivalent walls, and the gas may be air, provided the air volume is negligibly small. The essential requisite in this case is that the contribution to the ionization in the air made by ionizing particles originating in the air is negligible compared to that produced by ionizing particles characteristic of the wall material.

Tissue-equivalent material. Material made up of the same elements in the same proportions as they occur in some particular biological tissue. Such material is important in the construction of ionization chambers for neutron measurement. In some cases the equivalence may be brought about sufficiently closely without exact duplication of the elemental composition of the tissue. (See *Effective atomic number*)

Tolerance dose. A term based on the assumption that an individual can receive such a dose of radiation without any harmful effects. It is now superseded by *Permissible dose* (*q.v.*).

Tracer studies. Use of isotopically labeled material to investigate biological processes, chemical reactions, or physical phenomena. Either stable or radioactive isotopes can be used, in any desirable chemical form, but, in the case of radioactive tracers, the amount must be so small that the radiation will not interfere with the natural course of the process under study.

Volume dose. Integral dose (*q.v.*).

Volume ionization. Average ionization density in a given volume irrespective of the specific ionization of the ionizing particles.

X-rays. Penetrating electromagnetic radiations having wavelengths very much shorter than those of visible light. They are usually produced by bombarding a metallic target with fast electrons in a high vacuum. In nuclear reactions it is customary to refer to photons originating in the nucleus as gamma rays, and to those originating in the extranuclear part of the atom as X-rays. These rays were called X-rays by their discoverer, Roentgen. Many medical radiologists prefer to call them by his name; non-medical usage is generally X-rays.

UNITS

Curie. The quantity of radon in equilibrium with 1 gram of radium. By extension, the quantity of any radioactive element undergoing the same number of disintegrations per second as one curie of radon. This number is generally accepted as 3.7×10^{10}.

Microcurie (μc). One millionth of a curie.

Millicurie (mc). One thousandth of a curie.

Roentgen. That quantity of X- or gamma radiation for which the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying 1 esu of quantity of electricity of either sign.

The following is a supplementary list of units occasionally used by limited groups, but not having general acceptance.

Energy unit (a proposed unit; Gray). The dose received from ionizing radiation at a point in tissue when the energy absorbed is 93 ergs per gram at that point.

Equivalent roentgen (a proposed unit). (See *Roentgen equivalent, physical.*)

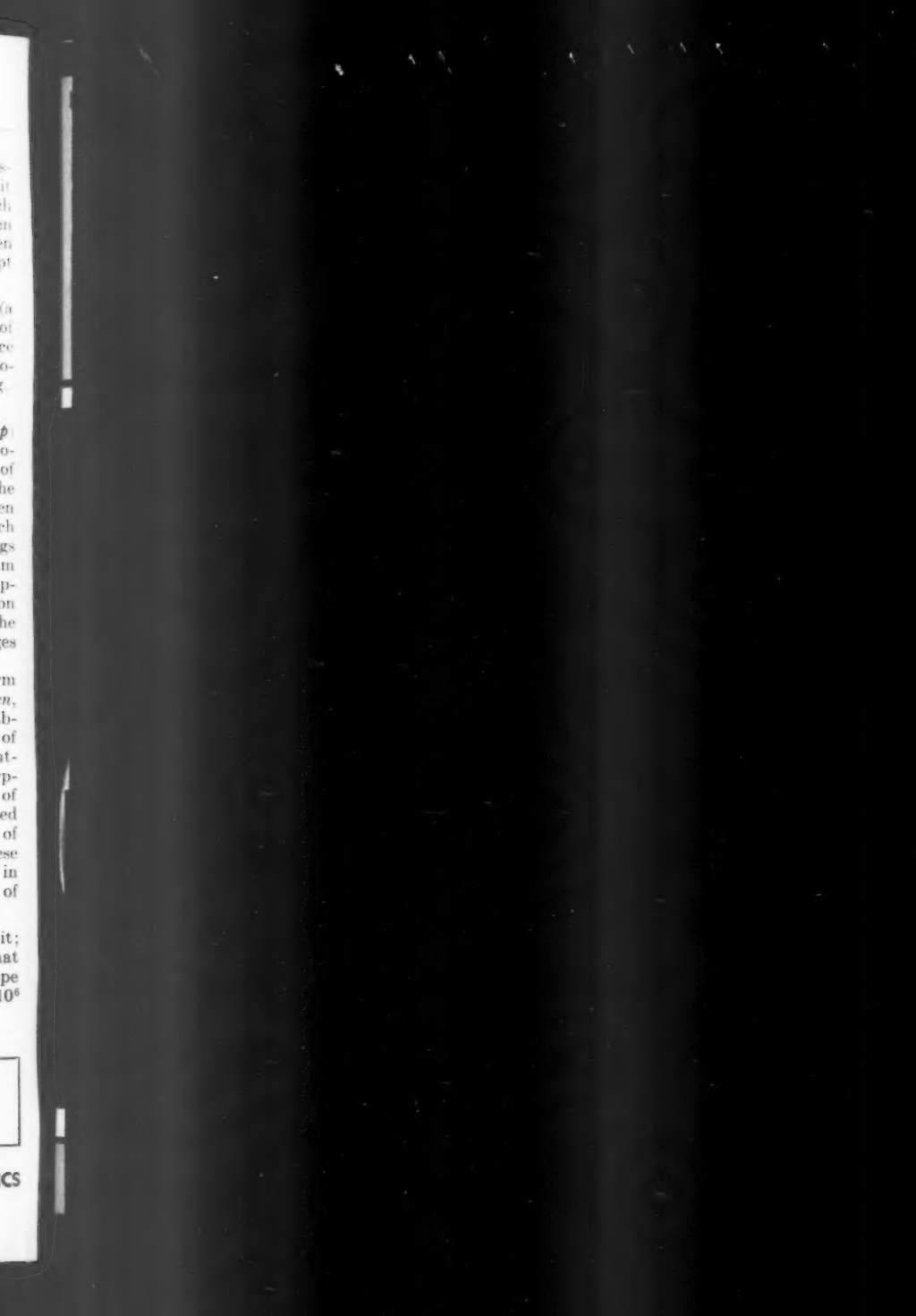
Gram-roentgen (a proposed unit; Mayneord). The unit is defined by Mayneord as the real energy conversion when a dose of one roentgen is delivered to one gram of air (about 84 ergs). The unit is employed, however, to describe total energy absorption by the patient in the course of therapy. The quantity obtained by integrating gram-roentgens throughout a region is called the integral dose (*q.v.*). Thus the integral dose, measured in gram-roentgens, resulting from irradiation of a patient with one roentgen of X-rays, will vary with the quality of the radiation, the size of the field, and the thickness of the part.

N-unit, n-unit. (These are not actually proposed units, but have been employed as convenient interim methods of specifying neutron doses until satisfactory units and methods of measurement can be devised.) The *n*-unit is that quantity of fast neutrons which will produce in a 100-r Victoreen r-meter the same reading as 1 roentgen of X-rays; the *N*-unit is the same except that the 25-r chamber is used.

Roentgen equivalent, man (***rem***) (a proposed unit; Parker). The dose of any ionizing radiation that will produce the same biological effect as that produced by one roentgen of high-voltage X-radiation.

Roentgen equivalent, physical (***rep***) (a proposed unit; Parker). A unit proposed to apply to statements of dose of ionizing radiation not covered by the definition of the roentgen. It has been variously defined as the dose which produces energy absorption of 83 ergs per gram of tissue or 93 ergs per gram of tissue. The actual energy absorption in tissue per roentgen is a function of the tissue composition and of the wavelength of the radiation, and ranges between 60 and 100 ergs per gram.

Various authors have used the term *roentgen equivalent* or *equivalent roentgen*, basing the equivalence on energy absorption by air, or on the number of ion pairs produced in air by one roentgen of X-rays, or on the energy absorption in tissue from one roentgen of X-rays, or on the ionization produced in a small air cavity by one roentgen of X-rays. The magnitude of all these units is the same within about 10%, in terms of energy absorbed per gram of tissue.

Rutherford (***rd***) (a proposed unit; Evans, Condon, and Curtiss). That amount of any radioactive isotope which disintegrates at the rate of 10^6 disintegrations per second.

NUCLEONICS will publish selections from the remaining seven sections of the Nuclear Energy Glossary as soon as the review committees make them available.